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Advanced Control for Airbreathing Engines

Volume 2

General Electric Aircraft Engines

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ADVANCED CONTROL FOR AIRBREATHING ENGINES

FINAL REPORT

JULY 1991

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Prepared For
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1. SUMMARY

An initial screening of advanced control features/concepts for airbreathing engines was performed to enable further detailed studies on the more promising concepts. Descriptions and block diagrams were developed for ten advanced control concepts which could impact turbine engine performance and operability in High Speed Civil Transport and High Performance Military Fighter applications. Figures of Merit were developed to measure the impact of each concept on performance, operability, control complexity, and life cycle cost.

A detailed evaluation of selected advanced control concepts based on the initial screening was performed to quantify the potential impact of each concept in terms of aircraft/engine performance, specific fuel consumption (SFC), take–off gross weight (TOGW) and direct operating costs (DOC). Due to the funding level available the evaluation was restricted to a High Speed Civil Transport, Mach 2.4 Mission application.

2. INTRODUCTION

The application of Advanced Controls to Airbreathing Engines offers potential for improvement of performance and operability. Detailed studies are planned as part of the Advanced Propulsion Technologies (APT) program, to provide detailed quantified measures of improvements for various engine control features as applied to several aircraft types (specifically, High Speed Civil Transport and Military High Performance Fighter). The purpose of this study is to perform a preliminary screening on the various control features/approaches/concepts, followed by a detailed evaluation of selected control concepts for a HSCT application only.

3. PHASE I

3.1. SELECTED CONTROL CONCEPTS

Ten control concepts which could impact turbine engine performance and operability were selected for consideration.

Active Burner Pattern Factor Control
Active Tip Clearance Control
Active Compressor Inlet Distortion Control
Active Jet Noise Suppression
Active Surge/Stall Control
Performance Seeking Control
Intelligent/Diagnostic Control
Secondary Cooling Airflow Control
Active Combustor Howl/Growl Control
Active Afterburner Rumble Suppression

A schematic block diagram and detailed description of each concept with effects on performance, operability, control complexity and life cycle cost is included in Appendix I. The following material briefly describes the objective of the concepts.

1) <u>Active Burner Pattern Factor Control</u> – This concept senses and controls hot streaks by modulating the fuel flow from individual combustor nozzle injectors. The objective is to operate at uniform fuel injector temperatures using temperature measurements at the exit of each fuel injector. This allows operation at higher average maximum temperature without reducing hot parts life.

2) <u>Active Tip Clearance Control</u> – This concept calculates turbine tip blade clearances using either an analytical model or sensor measurement and modulates cool-

ing/heating airflow to turbine casings to control the clearances. This improves High Pressure and Low Pressure turbine performance.

3) Active Compressor Inlet Distortion Control – This concept computes inlet distortion by modeling the aircraft's inlet characteristics in the digital control and controls sectors of variable compressor vanes to dissipate the effect of distortion on stall margin. The objective is to reduce stall margin requirements, allowing a higher design operating line or a fan/compressor redesign with associated weight reduction and increased compressor/fan efficiency.

4) Active Jet Noise Suppression – This concept senses near – field pressure oscillations, amplifies the error from a preset threshold, and uses acoustic drivers to inject a high frequency tone with the opposite phase into the turbulent jet in the engine tailpipe to reduce jet emission noise.

5) Active Surge/Stall Control – This concept senses a stall precursor and suppresses instability by controlling sectors of variable vanes or modulating bleeds, fuel flow and stator vanes. The objective is to permit stall/surge free operation with reduced design stall margin requirements.

6) Performance Seeking Control – This concept uses an on–line computer algorithm to fine tune steady–state control schedules to account for engine–to–engine variations (quality and deterioration), scheduling errors and off–nominal operating conditions. This reduces part–power SFC and permits a reduction in T41 temperature.

7) Intelligent Diagnostic/Control System – This approach optimizes schedules like Performance Seeking Control and adds capabilities to monitor the health of the en-

gine and control system, to accommodate faults in the engine and control system, including reconfiguration of the control when necessary. The objective of these features is to optimize performance, improve inflight shutdown rate (IFSR) and mission completion.

8) Secondary Cooling Airflow Control – High pressure and Low Pressure turbine blade temperatures are sensed and cooling air is modulated to control blade temperature. SFC is improved by providing less cooling for off–design operation.

9) Active Combustor Howl/Growl Suppression – This feature senses pressure oscillations and modulates main combustor fuel flow to suppress combustion instabilities. The payoff is reduced noise and increased main combustor life.

10) Active Afterburner Rumble Suppression – This concept senses pressure oscillations and modulates afterburner fuel flow to suppress combustion instabilities. Noise and afterburner liner weight are reduced while afterburner life is increased.

3.2. ESTABLISHMENT OF BASIS FOR COMPARISON

Two reference aircraft/engine combinations (a High Speed Civil transport and High Performance Military Fighter) were selected for use as a basis for comparative evaluation of the control concepts. The missions for these advanced VCE engine powered aircraft are shown in the Appendix, Figures 3.2–1 and 3.2–2.

Twelve engineers from Performance, Preliminary Design, Advanced Systems Analysis, and Controls organizations provided opinions on the relative importance of the four major categories of performance, operability, control complexity, and life cycle cost. The results, designated as PR, are shown in Appendix, Figure 3.2–3. They also participated in the selection and weighting of the subcategory criteria associated with the major categories, designated as In,i (Index showing relative weighting of element (i) of major category n. These results are shown in the Appendix, Figure 3.2–4. Average values were determined for use in the Figure of Merit calculations by deleting high and low numbers. A group of four Controls engineers and six Preliminary Design/Advanced Systems Analysis engineers then estimated the contribution of each candidate control concept with respect to each subcategory item . Finally, a Figure of Merit was determined for candidate control concept, shown in Appendix, page 8.

Figures 3.2–1 & 3.2–2 in the Appendix illustrate the resulting Figures of Merit for the High Speed Civil Transport and the High Performance Military Fighter respectively.

3.3. SCREENING OF CONTROL FEATURES

The advanced control concepts Figures of Merit and rankings from a performance, operability, control complexity, life cycle cost, and overall standpoint are summarized in the Appendix, Fig 3.3–1. Concepts with a high Figure of Merit numerical value are the candidates judged most likely to offer improvement in engine/aircraft operation. Thus the concept with the highest Figure of Merit value is ranked number 1 and the lowest is ranked number 10.

3.4. CONCLUSIONS

The ranking of control concepts as shown in the Appendix, Figure 3.3–1 may be conveniently divided into two groups (a high ranking top six and lower ranking bottom four). The six concepts in the higher score category are:

Performance Seeking Control (PSC)
Intelligent Diagnostic/Control System (IDCS)
Tip Clearance Control (TCC)
Secondary Cooling Airflow Control (SCAC)
Active Stall/Surge Control (SSC)
Active Compressor Inlet Distortion Control (CIDC)

These concepts scored in the top six group whether one considered either the High Performance Military Fighter or High Speed Civil Transport. These concepts scored higher because they were either less complex to implement, or contributed to several major categories in the ranking or both.

The acoustic concepts did not rank high overall because noise was only a part of one of the four categories, performance. The concepts would have achieved a higher ranking if they scored significantly in the other categories. In the case of active jet noise control, the potential complexity of the concept reduced its overall score, even though the concept could have a major beneficial impact on the engine sizing and operation for the High Speed Civil Transport.

The funding level available for Phase II of this Task Order restricts the application to the HSCT and also limits the number of concepts that can be studied. Assuming that control complexity can be brought to a reasonable level by further study of the enabling technologies, the above candidates will be considered.

4. PHASE II

4.1. SELECTED CONTROL FUNCTIONS

Preliminary screening studies identified six control functions which warranted further study. Secondary cooling flow was not considered for a HSCT application for the reasons described below. The remaining five control functions may be grouped into three concepts as follows:

Concept Ia) ACTIVE STALL/SURGE CONTROL
b) ACTIVE DISTORTION CONTROL

Concept II
a) ACTIVE TURBINE TIP CLEARANCE CONTROL

Concept III
a) PERFORMANCE SEEKING CONTROL
b) INTELLIGENT/DIAGNOSTIC CONTROL

The logic to the grouping is that the control concepts contained within each group have similar impact on how the engine would respond to the control concept. The response of the engine to the control concept is the subject of the next section.

For a typical commercial aircraft take–off is the design condition while for a HSCT type application cruise is the design operating point. As a result for a HSCT a reduction of secondary cooling flow to enable the engine to operate at higher temperatures is not possible. Examination of high pressure turbine design parameters T3 (compressor exit temperature) and T41 (turbine inlet temperature) as a function of mission profile for both HSCT and typical civil applications show that higher temperatures exist at "take–off" for subsonic aircraft while temperatures are higher at "cruise" for HSCT type applications. This is due to the higher ram inlet temperatures that are present in supersonic aircraft. Typical temperature profiles for both missions are shown in schematics Figs 4.1–1 and 4.1–2. This implies that "take–off" is the design operating point for subsonic civil applications and "cruise" is the design point for an HSCT. As a result the ability to raise the operating temperature by reducing secondary cooling flow inorder to improve SFC is not possible for a

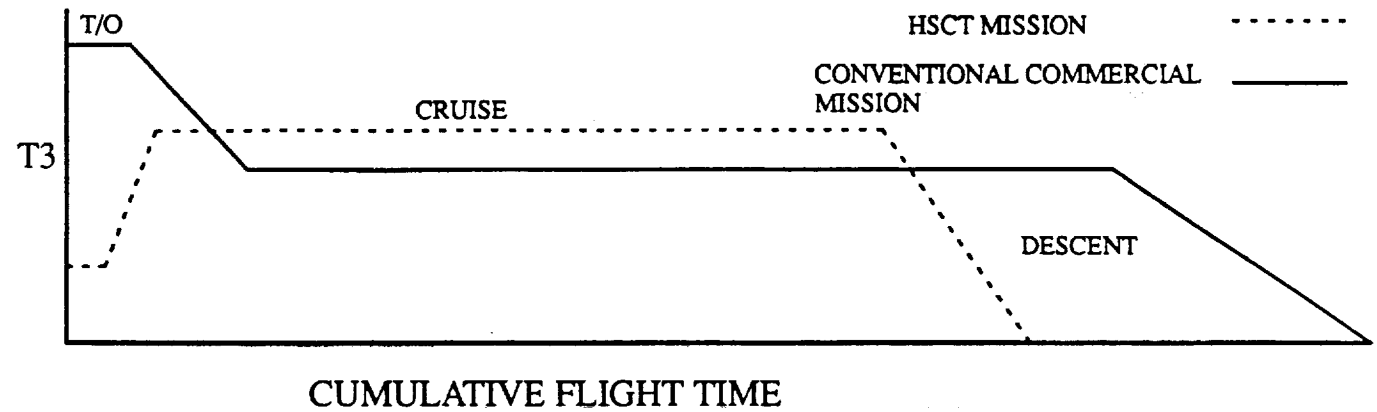
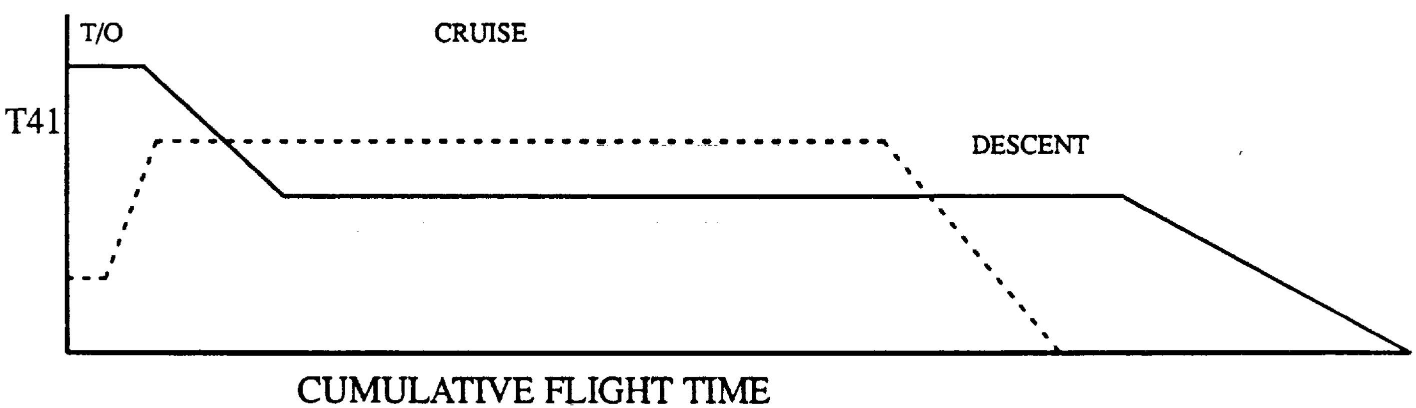


Fig 4.1–1 Typical T3 temperature profiles for HSCT and Conventional Commercial Missions

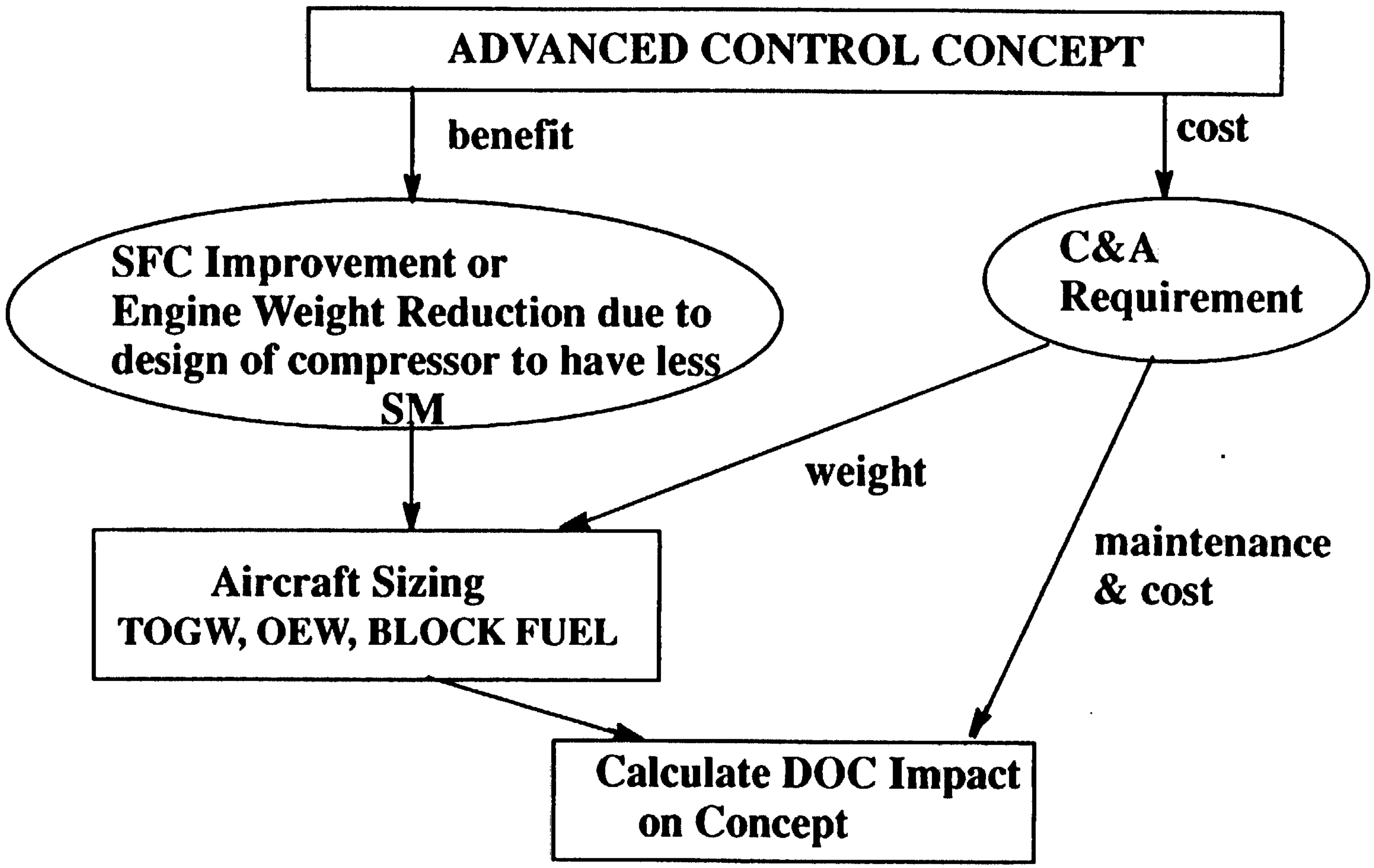


Typical T41 temperature profile

Fig 4.1–2 Typical T41 temperature profiles for HSCT and Conventional Commercial Missions

HSCT aircraft.

Figure 4.1–3 ADVANCED CONCEPT EVALUATION PROCESS



The advanced concept evaluation process used in phase II of the program is shown in Figure 4.1–3. Each concept was evaluated for the benefits to be obtained in terms of SFC improvement or engine weight reduction due to a reduced compressor design margin requirement, and overall cost. The results from this analysis were then used to determine the impact on aircraft sizing and direct operating cost for each concept.

4.2. IMPACT OF CONTROLS CONCEPT ON ENGINE OPERATION

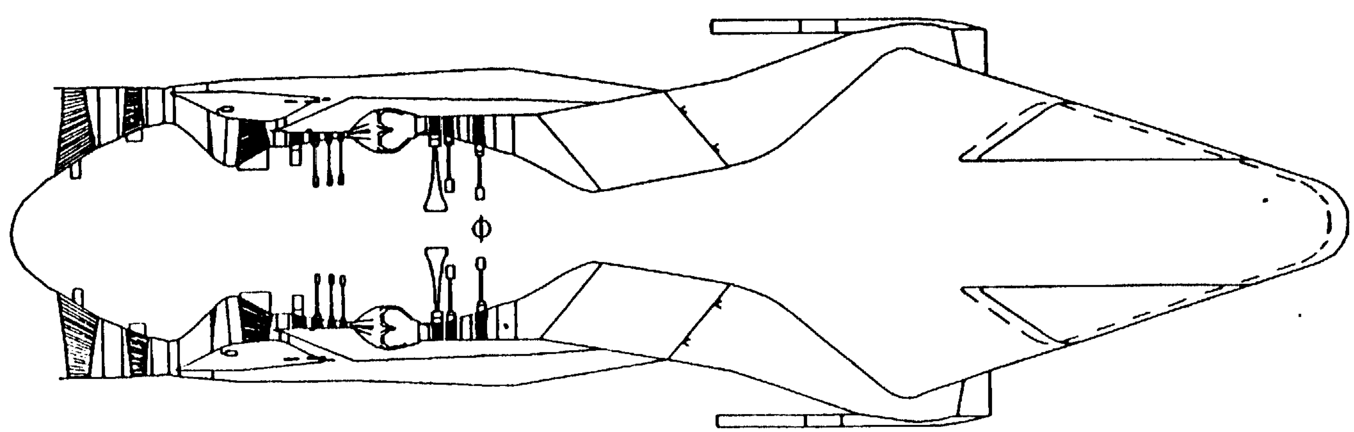
4.2.1. Concept I

The baseline HSCT engine selected for this study is a variable cycle turbofan shown in Figure 4.2. It was set up to operate within a pre–selected set of limits and design requirements. The applicable set of limits within this controls study effort are a) take–off jet velocity limited to abide by noise restrictions, b) compressor exit temperature as imposed by material limits and emissions limitations, and c) turbine inlet temperature as imposed by material limits. The design requirements of a) aircraft cruise and take–off thrust requirements and b) inlet airflow schedule were co–established with airframers that are currently studying HSCT aircraft.

The normal method of achieving a reduced stall margin is to raise the operating line on the component in question. In the case of the compressor operating line this requires the reduction of the high pressure turbine flow function and for the fan operating line the closure of the exhaust nozzle area (assuming an increase in turbine rotor inlet temperature is possible). These options are not available on the selected HSCT engine because it would require the engine to exceed design limits.

FIGURE 4.2 ENGINE SUMMARY
MACH 2.4 VCE ENGINE IOC 2005
GE21/F14 STUDY L1

INLET CORRECTED AIRFLOW - LB/SEC	700
OVERALL FAN PRESSURE RATIO	4.8
OVERALL CYCLE PRESSURE RATIO	25
MAXIMUM COMPRESSOR EXIT TEMPERATURE - °F	1320
MAXIMUM TURBINE ROTOR INLET TEMPERATURE - °F	3200
NOMINAL BYPASS RATIO	0.65



The limits are 1) Max T3 limit, 2) Jet velocity limit, 3) Fan mass flow requirement, 4) Core size and 5) Fan pressure ratio requirement. If the available stall margin is lowered, the high pressure turbine flow function is reduced. This will increase the cycle overall pressure ratio and at top–of–climb, where maximum T3 condition occurs, the pre–defined T3 limit will be exceeded. The fan is sized at take–off (T/O) where jet velocity is limiting; the required T/O thrust divided by the noise limiting jet velocity is the mass flow required by the fan. The inlet airflow schedule coupled with the top–of–climb thrust requirement, and the desire to operate dry, combine to determine the core size and the fan pressure ratio requirement. At T/O, the engine operates well below its maximum dry thrust potential. Raising fan operating line would increase jet velocity at takeoff (a limit), reduce propulsive efficiency at cruise (undesirable) and, because of higher supercharging, raise cycle overall pressure ratio at cruise (and further aggravate the T3 limit).

A logical alternative to raising the component operating lines is to drop the component stall line and reduce the weight of the components. The technique employed to reduce weight was to increase aspect ratio and reduce solidity without permitting efficiency deterioration. The details of this are discussed in Section 5.0.

4.2.2. Concept II

It is a well established fact that turbine efficiency improves as blade end clearance is reduced. The technique employed was to convert a change in clearance to a change in efficiency, using appropriate derivatives, and to determine a change in supersonic and subsonic specific fuel consumption, at thrust, using the cycle model for the selected engine. The details of these calculations are presented in Section 6.0.

4.2.3. Concept III

The cycle model that predicts the performance for the selected engine is considered to be the "nominal new engine". It is an engine wherein the performance of each component achieves the design intent. The schedules for the engine are initially selected to obtain the best performance within these component goals and representations. As actual engines are assembled from production components and as engine deterioration occurs due to accumulation of operating time, the performance representations for the components are altered which result in a degradation of overall engine performance. The basic idea for this concept is to reschedule the variable geometries within the engine to achieve the best possible engine performance consistent with the capabilities of the individual components as determined from on–line measurements. In principle this technique will enable restoration of a portion of the performance loss. The performance improvement selected due to this premise is presented in Section 7.0.

4.3. C&A COMPONENT REQUIREMENTS FOR SYSTEM CONCEPTS

The advanced control concepts described in the preceding paragraphs require additional controls and accessories (C&A) hardware and software in order to be implemented. The assumptions utilized in determining the cost, weight, maintainability and reliability of these requirements are described below. The weight, cost, maintainability and reliabilty for each concept were derived from the existing C&A data base. Cost and weight are self explanatory. Reliability is expressed in terms of failures per million engine flight hours (FPMH). Maintainability is expressed in terms of maintenance man hours (MMH) and can be divided into two (2) subcategories – Organizational Level and Intermediate Level maintenance. Organizational maintenance or "O" Level will perform preventative and corrective maintenance, servicing, cleaning, and replacement of engine Line Replaceable Units (LRU's), and Line Replaceable Modules (LRM's) for control and accessories determined to be defective using the diagnostics/fault isolation features of the engine monitoring system. Intermediate maintenance or "I" Level will perform Module, Shop Replaceable Unit (SRU) and LRU replacement, and repair components as much as practical by component replacement. Typically in controls and accessories "I" Level consists of cleaning, preserving, and shipping preparation. Fundamentally, MMH for controls and accessories is the time required to remove, install and prepare/preserve a line replaceable unit. It should be noted that implementing some of the concepts may require that some actuators be located 360 degrees circumferentially around the engine. This may potentially restrict easy access to some of the LRU's thus increasing the removal time.

Two assumptions were made in defining the component requirements. Firstly new technology items were extrapolated from the existing data base utilizing engineering judgement. Secondly since the HSCT Mach 2.4 VCE L1 engine is currently not configured with inlet guide vanes, it was assumed the hardware weight, cost, reliability and maintenance associated with the IGV's are included elsewhere.

4.4. HSCT AIRCRAFT SIZING STUDY

The figure of merit for the HSCT Controls Study is shown through aircraft Direct Operating Cost (DOC), reference Section 4.5. The effect of each control concept on aircraft takeoff gross weight (TOGW), operating empty weight (OEW), engine size (ie Sea Level Static Thrust) and block fuel is determined in this portion of the HSCT Controls Study through aircraft sizing. From these parameters, along with the changes in engine price and maintenance, as affected by each control system concept, the DOC/trip relative to a baseline can be determined.

4.4.1. Aircraft Sizing Methodology

A Mach 2.4 HSCT simulating the Boeing design is used in the study. The criteria used in developing the model are shown in Table 4.4–1. The representative GE21/F14 Study L1 VCE study engine characteristics are given in Table 4.4–2. Figures 4.4–1 and 4.4–2 show a sketch of the configuration and schematic of the mission used. The aircraft sizing procedure used by GEAE is shown schematically in Figure 4.4–3. This procedure incorporates the NASA takeoff trajectory code developed by W.E. Foss (Ref. 2). Typically, for the HSCT model used, criterion defining aircraft size are take–off field length (TOFL) and sideline noise along with the mission profile. With the above HSCT model, a representative two dimensional convergent/divergent (2DCD) nozzle with the potential to meet FAR Stage III noise requirements is used in the study. Sideline and community noise predictions are given as functions of mass averaged nozzle exit velocity. Integration of the GEAE aircraft sizing code along with the NASA takeoff trajectory code allows for the quick and accurate sizing of an aircraft considering the critical environmental constraint of noise. The referee flow size used for the engine is 700 lbs/sec. This flow size is considered to be Scale 1. and is adjusted according to aircraft requirements. The take–off sideline noise requirement required rescaling of the engine by 27%. to give a scale factor of 1.27 from the baseline.

Table 4.4–1 AIRCRAFT DESIGN CRITERIA

- Aircraft initial operating capability, or certification date: 2005
- Passenger/baggage capacity of 250 (payload = 51,900 lbs)
- Mission range = 5000 nautical miles, plus reserves
- Meet FAR–36, Stage III requirements
- Meet balanced field length of 11,000 ft on a +18°F day at design TOGW

Table 4.4–2 ENGINE CHARACTERISTICS, MACH 2.4 DESIGN, GE21/F14 STUDY L1 VCE

Initial Operating Capability	2005
Airflow, Corrected	700 lbs/sec
Overall Pressure Ratio	25
Bypass Pressure Ratio	0.645
Fan Pressure Ratio	4.7
Turbine Inlet Temperature	3200°F
T3	1300°F
Thrust/Weight(max) at Vj (Jet Velocity)	5.3 at 3128 ft/sec
Specific Net thrust at Vj	87.3 lbf at 3128 ft/sec
Thrust/Weight Acoustic at Vj	4.4 at 2800 ft/sec
Specific Net Thrust at Vj	71.4 lbf at 2800 ft/sec

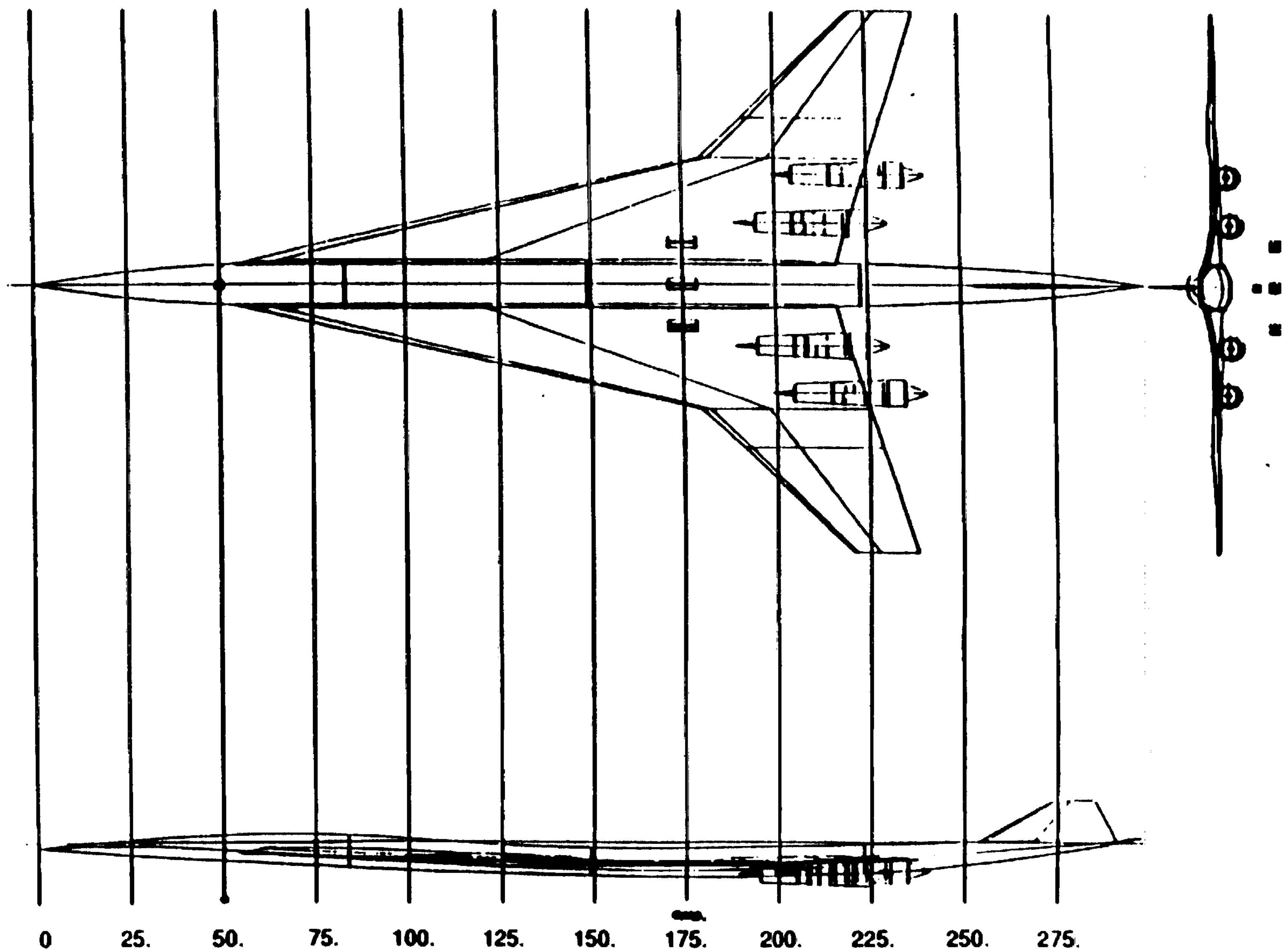


FIGURE 4.4-1 **Mach 2.4 HSCT Planform.**

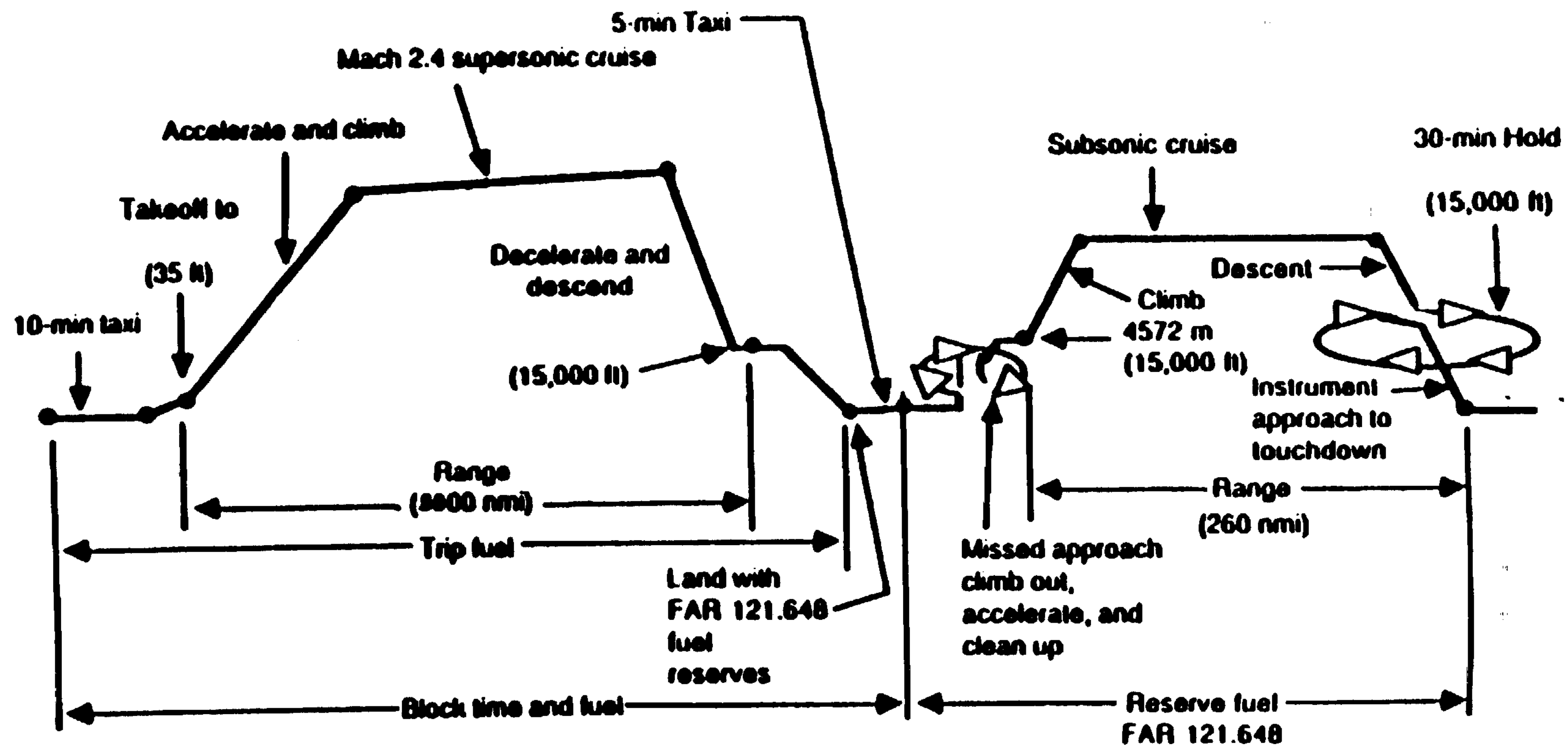


FIGURE 4.4-2 **Mission Definition.**

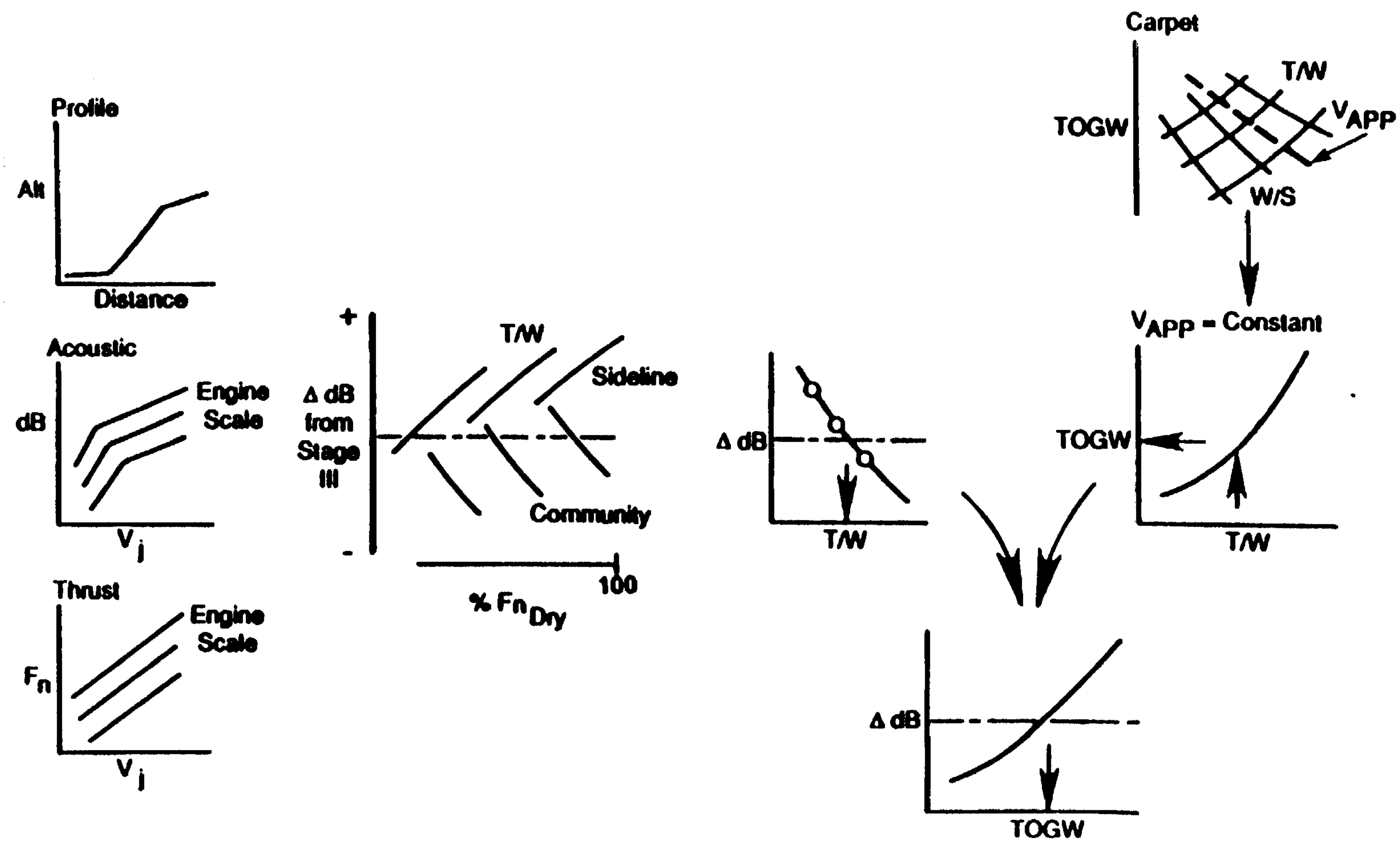


FIGURE 4.4-3 **Acoustic Sizing Routine.**

4.5. DIRECT OPERATING COST MODEL

The Direct Operating Cost (DOC) measure of merit for the HSCT Controls Study was based on a computerized version of the formulas published by the Air Transport Association (ATA) in 1967 and modified in 1979 by a major commercial air–frame manufacturer. The ATA method is the standard generic method used to calculate DOC and it includes the major cost elements incurred by the airlines. The DOC methodology and the interactions of the various elements are shown in Figure 4.5–1. The DOC ground rules and baseline inputs are shown in Table 4.5. The DOC model consists of 8 major elements as shown in Figure 4.5–1, but for illustrative purposes engine material maintenance, engine interest and engine depreciation have been broken out in the baseline DOC result (Figure 4.5–2). The study parameters which varied, predominantly influenced the fuel, engine material maintenance, engine depreciation and engine interest elements of the DOC model. These four elements accounted for 57.5% of the total DOC for the baseline case. The fuel portion was based on a $0.65/US Gallon fuel price since this corresponded to the pre–Desert Storm fuel price in 1990 dollars. Since fuel is the largest piece of the DOC pie (38.4%), a variation in fuel price can alter the DOC results significantly. Although engine maintenance due to materials changed for the various concepts studied, the impact of engine maintenance due to labor had minimal influence on the DOC results. Both engine depreciation and engine interest are based on engine acquisition cost. The acquisition cost (sell price) is the manufacturing cost plus an appropriate business margin.The advanced controls concepts studied varied the weights, manufacturing costs, maintenance costs and fuel burns of the aircraft systems (Figure 4.5–3). The DOC inputs affected were Takeoff Gross Weight

FIGURE 4.5-1 **DOC ELEMENTS**

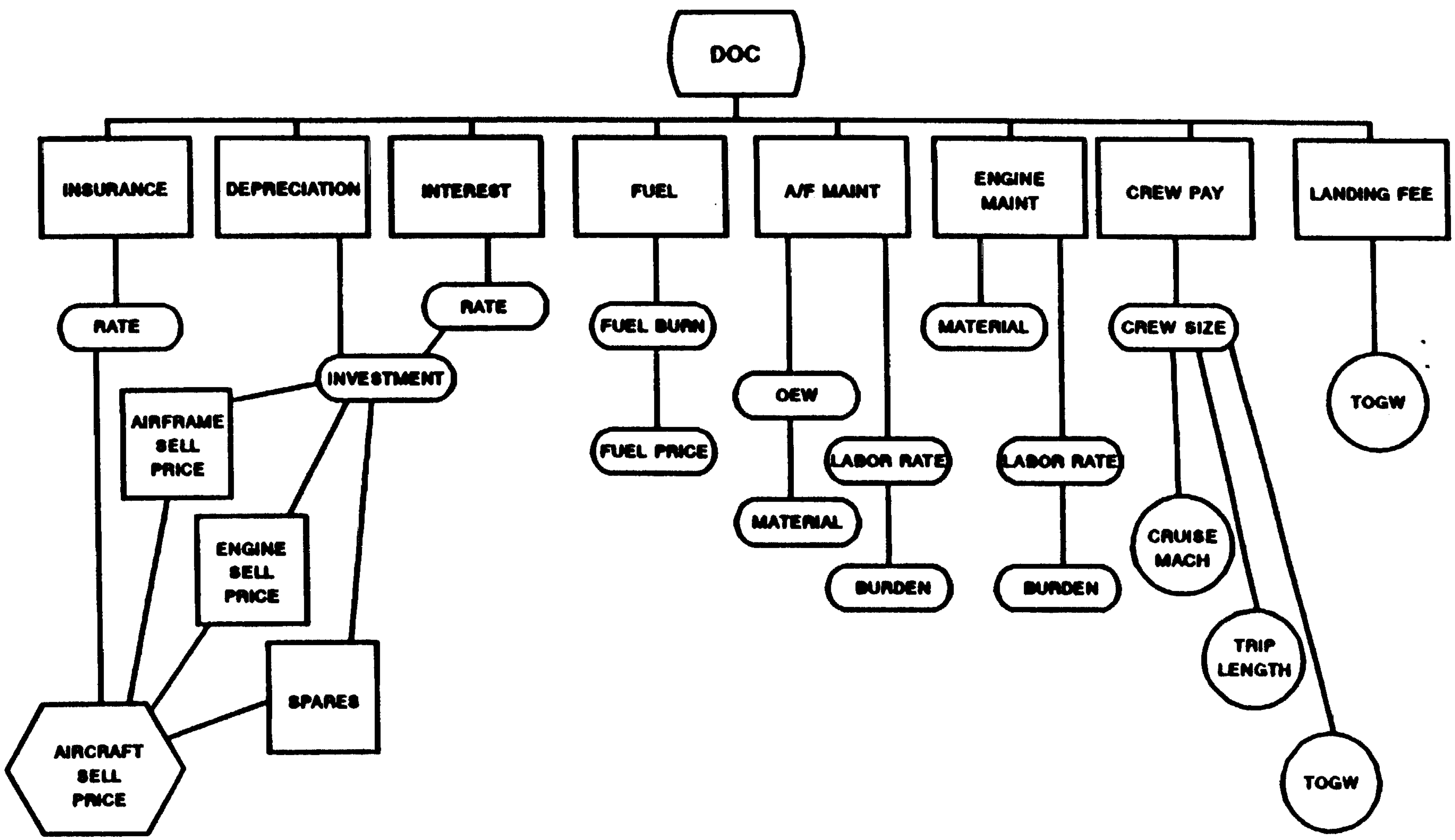


TABLE 4.5 **DOC INPUTS**

- ***DOC GROUND RULES:***

YEAR DOLLARS	1990
BLOCK TIME (hr)	4.1
STAGE LENGTH (nm)	5000
AIRCRAFT DEPRECIATION PERIOD (yr)	15
AIRCRAFT RESIDUAL VALUE (%)	10
UTILIZATION (Trip/yr)	760
INSURANCE (% OF INITIAL AIRCRAFT PRICE/yr)	0.5
INTEREST RATE (%/yr)	12
FINANCE PERIOD (yr)	15
BORROWED INVESTMENT (%)	90
LABOR RATE ($/hr)	16.00
MAINTENANCE BURDEN (%)	200
GROUND MANEUVER TIME (min)	14
PASSENGERS	275
FUEL PRICE ($/US Gallon)	0.65
CREW	3
AIRFRAME SPARES (% OF AIRFRAME PRICE)	6
PROPULSION SYSTEM SPARES (% OF PROP SYS PRICE)	30
CRUISE MACH	2.4

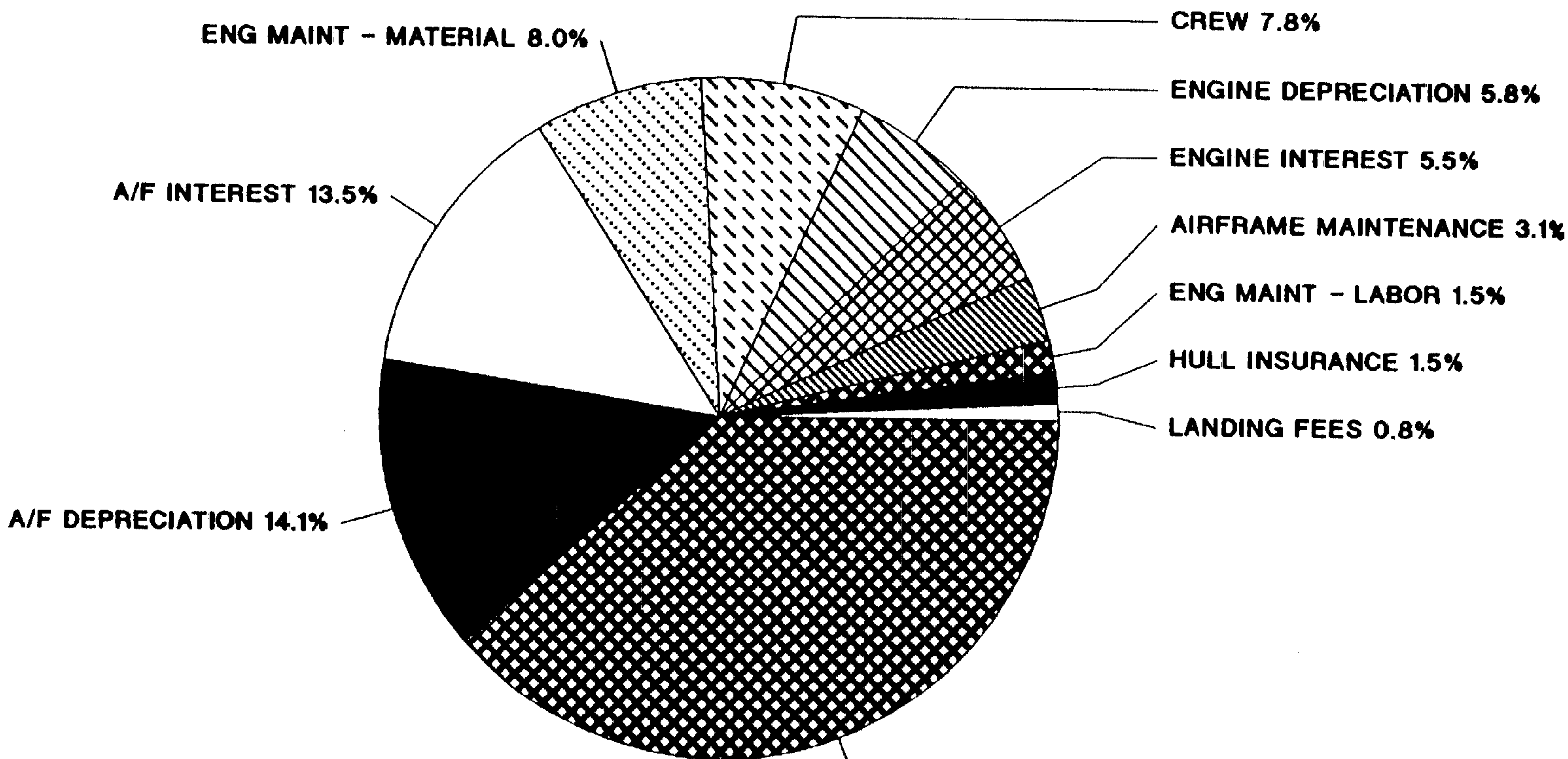
- ***BASELINE INPUTS***

TOGW (lb)	768,966
BLOCK FUEL (lb)	352,864
AIRFRAME PRICE ($ MILLION)	150.0
PROPULSION SYSTEM PRICE ($ MILLION)	12.5
OEW (lb)	327,950
PROPULSION SYSTEM MATERIALS COST ($/EFH)	461.16
LABOR INDEX (MH/EFH)	1.83

FIGURE 4.5-2 **BOEING REVISION OF ATA METHOD**

BASELINE HSCT DIRECT OPERATING COST BREAKDOWN

12% INTEREST RATE - 1990 DOLLARS - FUEL = $0.65/US GAL - 5000nm - 760 TRIPS/YEAR



NOTE: UTILIZATION IS TWICE THE SUBSONIC RATE

FIGURE 4.5-3 **INPUT MODIFICATIONS TO DOC FOR ADVANCED CONTROLS CONCEPTS**

CONCEPT	DELTA MANUFACTURING COST ($/eng)	DELTA MAINTENANCE ($/EFH)	DELTA FUEL BURN (%)
• BASELINE	BASE	BASE	BASE
• ACTIVE STALL/SURGE	125.3K	12.87	-0.11
• INLET DISTORTION	55.7K	14.66	-0.60
• ACTIVE TIP CLEARANCE	14.9K	0.36	-1.22
• PERFORMANCE SEEKING	2.2K	NONE	-4.19
• INTELLIGENT DIAGNOSTIC	30.0K	9.09	-4.19

(TOGW), Operating Empty Weight (OEW), Sea Level Static thrust, engine price, block fuel, engine material cost and engine labor index.

5.0 CONCEPT I – ENGINE WEIGHT REDUCTION DUE TO REDUCED STALL MARGIN REQUIREMENT

5.1 ACTIVE STALL/SURGE CONTROL

This section deals with an effort to quantify the weight savings resulting from a reduced compressor stall margin requirement due to active stall/surge control. Three GEAE computer programs were utilized to perform this study: EASY–OPT (an optimization tool), FLOWPATH (an engine design and weight estimation code) and CUS5 (a code for evaluating efficiency and stall margin for a specific hardware configuration). EASY–OPT was coupled to FLOWPATH and CUS5 to allow stall margin to be traded against compressor weight. The baseline compressor for this study was a 4 stage core compressor making a pressure ratio of 4.0 with a CUS5 estimated efficiency of 87.7%. The following constraints were placed on the problem:

– Aspect ratio and solidity were allowed to vary up or down by 0.2 counts from the baseline design

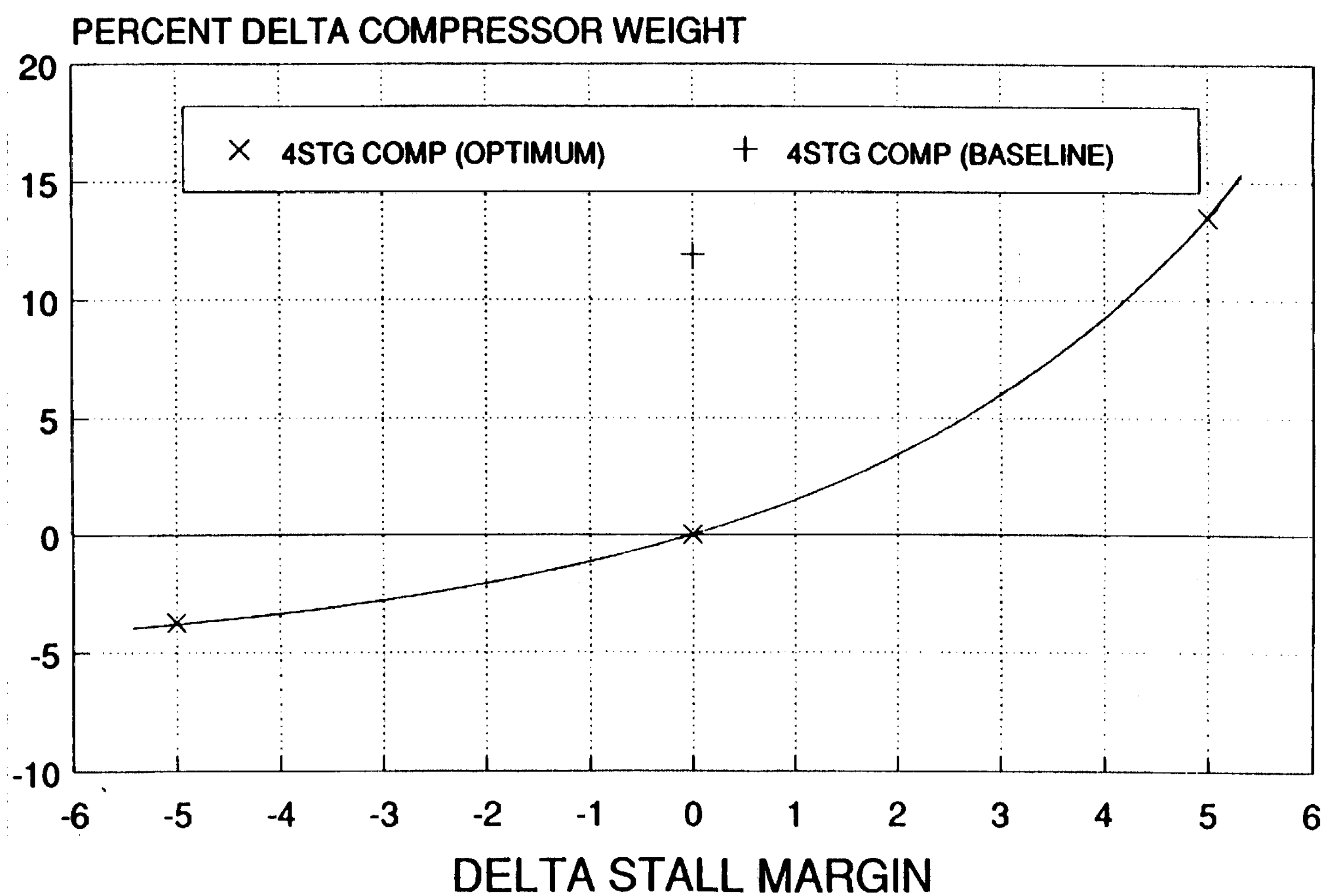
– Efficiency predicted by CUS5 was required to be greater than 87.5%.

– Compressor rotor and stator diffusion factors could not exceed 0.5.

The optimization program was set up to minimize compressor weight (by varying aspect ratio and solidity), while maintaining the above listed constraints for a specified level of stall margin. The impact on weight of a reduction in stall margin while holding efficiency and varying solidity aspect ratio parameter (SARP) is shown in Fig 5.1. The results show that within the stated design constraint a 5 percent reduc

FIGURE 5.1

STALL MARGIN IMPACT ON WEIGHT
(HOLDING EFFICIENCY & VARYING SARP)



–tion in stall margin requirement results in a 4 percent compressor weight savings whereas a 5 percent increase in stall margin requirement resulted in a weight increase of 13.5 percent.

An analytical study of the active stabilization of multistage compressors at GE (ref 3) indicate a reduction of 3% in fan stall margin and 3% in compressor stall margin is possible with the utilization of active stall/surge control.

5.1.1 Component Requirements for Active Stall/ Surge Control (Concept 1a)

At the start of this study, the quantity of bleed flow modulation, fuel flow modulation, stator vanes deviation, and response requirements were not defined. As a result, several assumptions were made at that time.

First, only the high pressure compressor variable stators would be configured with active stall/surge control hardware. Second, the stall precursor can be accurately estimated utilizing four (4) high response pressure transducers located circumferentially around stages 1, 2, and 3. Third, the current bleed and fuel delivery systems are satisfactory for delivering the desired bleed and fuel flow modulation, and therefore no additional hardware is required. Fourth, multiplexing pressure signals is unacceptable due to sensor loop bandwidth requirements and therefore the pressure sensors will be located directly on the engine. Finally, each stator segment will be configured with a hydraulic actuator fitted with a large capacity servo valve, pressure transducer and position feedback coupled to an independent core variable stator vane (CVSV) control module. The larger servo valve will increase the frequency response of a conventional hydraulic actuator to 10 Hz which is assumed adequate. The CVSV control module communicates with the FADEC over a data bus to decouple the active stall/surge control loop requirements from the other FA-

DEC requirements. Finally, the frequency response for the bleed, fuel, and stator vane modulations were assumed to be +/– 10% full stroke at 10 Hz.

The cost, weight and maintenance associated with implementing Active Stall/ Surge Control are defined in Table 5.1–1

Table 5.1–1. Concept I(a): Active Stall/Surge Control		
Weight:		Total
Actuator Assembly (16)	132.8	
– Actuator w/LVDT		
– Servo Valve		
– Pressure Transducer		
– Ring Segment/Bellcrank		
CVSV Control Module	15.0	
		147.8 lbm
Cost:		
Actuator Assembly (16)	$ 109.3K	
CVSV Control Module	$ 16.0K	
		$ 125.3K
Maintenance:	MMH	LRU (F/10**6)EFH
Actuator Assembly (16)	0.4	43.1
CVSV Control Module	0.5	250.0

5.1.2 Aircraft Sizing Results

The active surge/stall control concept impacts the engine system through a reduction in fan and compressor stall margins (SM). The reductions considered were 3 percent for both fan and compressor. These figures were based on studies performed at GE Aircraft Engines and documented in Ref 3. Translating these reductions into potential reductions in fan and compressor weight through redesign allowed for a reduced engine weight of 157 lbs at the cycle 700 lbm/sec flow size (scale 1). Additional control system weight was +148 lbs for a total reduction at scale 1 engine size of 9 lbs. This concept does not effect engine SFC. From Table 8.1 a calculated 0.1 percent reduction in TOGW through aircraft resizing is seen. (Note: Scale 1, refers to the nominal engine size. This is resized according to noise, aircraft thrust/weight requirements, take–off field length.)

5.1.3 Direct Operating Results

The Active Surge/Stall Control concept produced the largest weight and manufacturing cost increases due to the requirement of having 16 actuators located circumferentially around the engine to control engine stall. This requirement combined with the lowest fuel burn savings of the five concepts studied, results in the highest DOC. The engine material maintenance cost as well as the increased acquisition cost far outweighed the slight fuel burn reduction to produce a $395/trip (+0.44%) increase in DOC as shown in Figure 8–1. A fuel price of $7.35/US Gallon would be necessary to produce equal DOC with the baseline.

5.1.4 Results Summary for SSC

The improvements to be obtained when using Active Stall/Surge control compared with the baseline engine are :–

Delta Manufacturing Cost ($/eng)	125.3K
Delta Maintenance ($/EFH)	12.87
Delta Fuel Burn (%)	–0.11

Delta Engine Size (%)	–0.1
1000 Fleet Delta DOC/Year ($ Million)	300.1

5.2 INLET DISTORTION CONTROL (IDC)

The flow nonuniformity at the compressor face (inlet distortion) reduces compressor stall margin and directly impacts compressor design. The implementation of sector control of fan and compressor inlet guide vanes and variable stators is used to improve engine performance when subject to inlet distortion. The process increases fan/compressor performance and distortion tolerance through compensation for inlet distortion. The result is increased thrust and improved SFC by operating at a higher pressure ratio with a lower stall margin. The efficiency benefits to be obtained from IDC are very small and can be ignored. The benefits from IDC can be realised by reduced weight in a similar manner to active/stall surge control. The potential reductions in stall margin are 4% for the fan and 3% for the compressor. The reduction in fan stall margin is slightly larger than with active/stall surge control due to compensation for inlet distortion.

5.2.1 Component Requirements for IDC

Implementation of Active Inlet Distortion Control on HSCT will require eight independently actuated fan IGV segments integrated with an existing hydraulic system. The response rates of these actuation segments are assumed to be typical of current production actuators. The segmented fan IGV's are manipulated/controlled by an Integrated FIGV Control System which features a hydromechanical multiplexer and electronic controller. The IGV segments will be controlled as a function of corrected airflow and circumferential distortion index (IDC). IDC is calculated in the FADEC as a function of alpha angle, beta angle (yaw), Mach number, and corrected airflow. The cost, weight and maintenance associated with implementing Active Inlet Distortion Control are defined in Table 5.2–1.

Table 5.2–1 Concept I(b): Active Inlet Distortion Control		
Weight:		Total
Actuator Assembly (8)	40.8	
– Actuator w/LVDT		
– Configuration		
– Ring Segment/Bellcrank		
Servo/Hmux	8.7	
FIGV Control Module	15.0	
		64.5 lbm
Cost:		
Actuator Assembly (3300*8)	$ 26.6K	
FIGV Control Module	$ 16.0K	
Servo/Hmux	$ 13.1K	
		$ 55.7K
Maintenance:	MMH	LRU (F/10**6)EFH
Actuator Assembly (16)	0.4	43.1
FIGV Control Module	0.5	250.0
Servo/Hmux	0.2	59.5

5.2.2 Aircraft Sizing Results for IDC

The inlet distortion control affects engine system weight only and again the benfit is realized through reduced fan and compressor stall margins. A 4% reduction in compressor SM and 3 percent reduction in fan SM were considered. These reductions translate to a potential 196 lbs reduction of engine weight at scale 1. Additionally the inlet distortion control system hardware adds 65 lbs at scale 1, for a total of 131 lbs reduction at scale 1. Through aircraft resizing, a potential reduction of 0.6 percent in TOGW over baseline may be realized, see Table 8.1.

5.2.3 Direct Operating Cost Results for IDC

The Inlet Distortion control concept had smaller weight and manufacturing cost increases than the Surge/Stall concept and produced a lower fuel burn, therefore, the DOC was reduced. However, when compared to the baseline case, this concept was still \$113/trip (+0.13%) higher in DOC. As shown in Figure 8.1, the increased maintenance and acquisition costs negated the fuel burn advantage. A fuel price of \$1.01/US Gallon would be necessary to produce equal DOC with the baseline.

5.2.4 Results Summary for IDC

The improvements to be obtained when using Inlet Distortion Control as compared with the baseline are :–

Delta Manufacturing Cost (\$/eng)	55.7K
Delta Maintenance (\$/EFH)	14.66
Delta Fuel Burn (%)	–0.60
Delta Engine Size (%)	–0.70
1000 Fleet Delta DOC/Year (\$ Million)	85.90

6.0 ENGINE SFC IMPROVEMENT DUE TO REDUCED TURBINE TIP CLEARANCE

6.1 ACTIVE TURBINE TIP CLEARANCE CONTROL

The loss in turbine efficiency associated with leakage through the tip is expressed as a function of percent clearance, which is the radial tip clearance gap non–dimensionalized by the rotor blade height. The rotor blade height is taken as the average between the leading and trailing edge heights. Thus, if a blade is 1.7″ in average height, one percent clearance would be defined as 0.017″ radial clearance gap.

The loss due to tip clearance is comprised of two parts. First, the flow that leaks through the clearance gap effectively bypasses the rotor, resulting in lost work. Secondly the leakage flow causes a loss in momentum when it reenters the gaspath and mixes.

The so–called tip clearance derivative is the loss in turbine stage efficiency caused by a one–percent change in tip clearance. Measured tip clearance derivatives for GEAE turbines vary from 1.2 points per percent for low reaction turbine stages to nearly three times that for high reaction stages. Quoted derivatives are based on scale model tests of turbine rigs where precise control of clearance and good measurements of efficiency are easier than in engine tests.

For multistage turbines, derivatives are quoted for each stage and are the effect of a one percent change in clearance for that stage on overall group efficiency. Thus, for a two–stage turbine, derivatives are about one–half of that for a single stage.

For the turbines in this study, the clearance derivative on the moderate reaction HPT is 1.83 and the blade height is 3.7". Thus a 0.010" change in clearance will cause a decrease in HPT efficiency of 0.01/3.7*1.83, or 0.005. This is one–half point in efficiency.

The derivatives on stage 1 and stage 2 of the LPT are 0.62 and 0.64 respectively, showing that the lightly loaded LPT is much less sensitive to clearance. These results are summarized :–

	HPT	LPT	
	Stage 1	Stage1	Stage2
Blade Height (ins) h	3.7	4.3	6.2
Clearance Derivative	0.0183	0.0062	0.0064
Delta Efficiency for 0.010 change in clearance	0.005 (0.5 pts)	0.0014 (0.14 pts)	0.0010 (0.10 pts)

The cycle model for the HSCT–L1 engine was used to calculate the change inuninstalled specific fuel consumption for turbine efficiency improvements of 0.5 pt on the HPT and 0.24 pt on the LPT. These sensitivities were calculated at a range of power settings for both subsonic and supersonic cruise. They were found to be relatively constant in the cruise regions, as shown in Figures 6.1 and 6.2 The results are summarized below:

FIGURE 6.1 SUPERSONIC CRUISE SFC COMPARISON

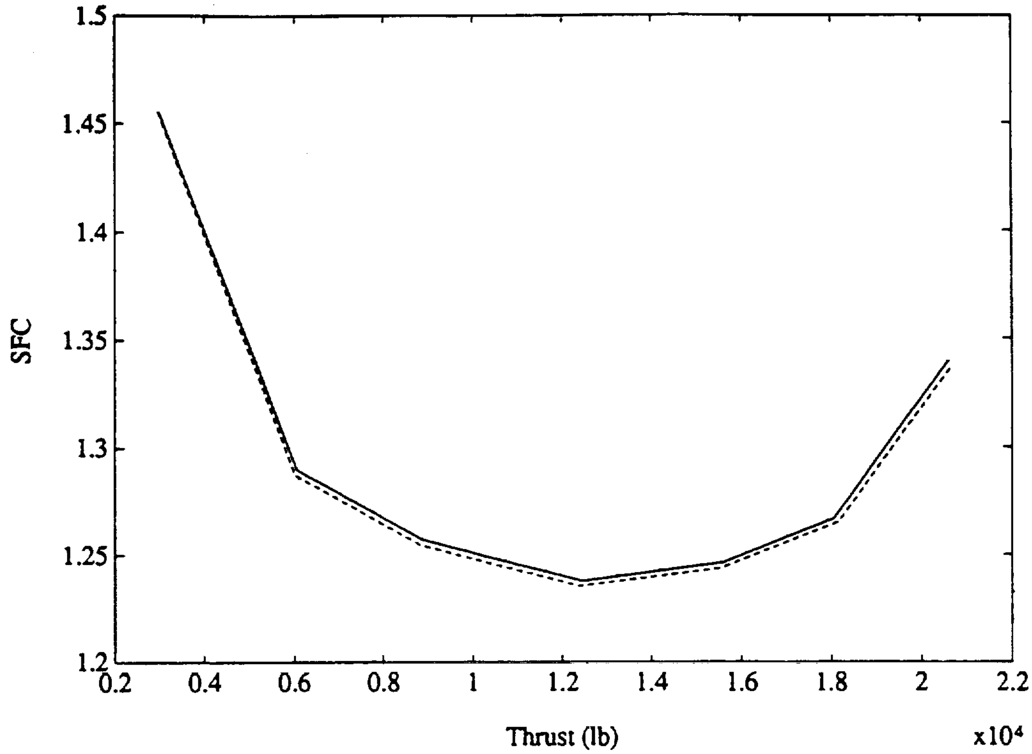
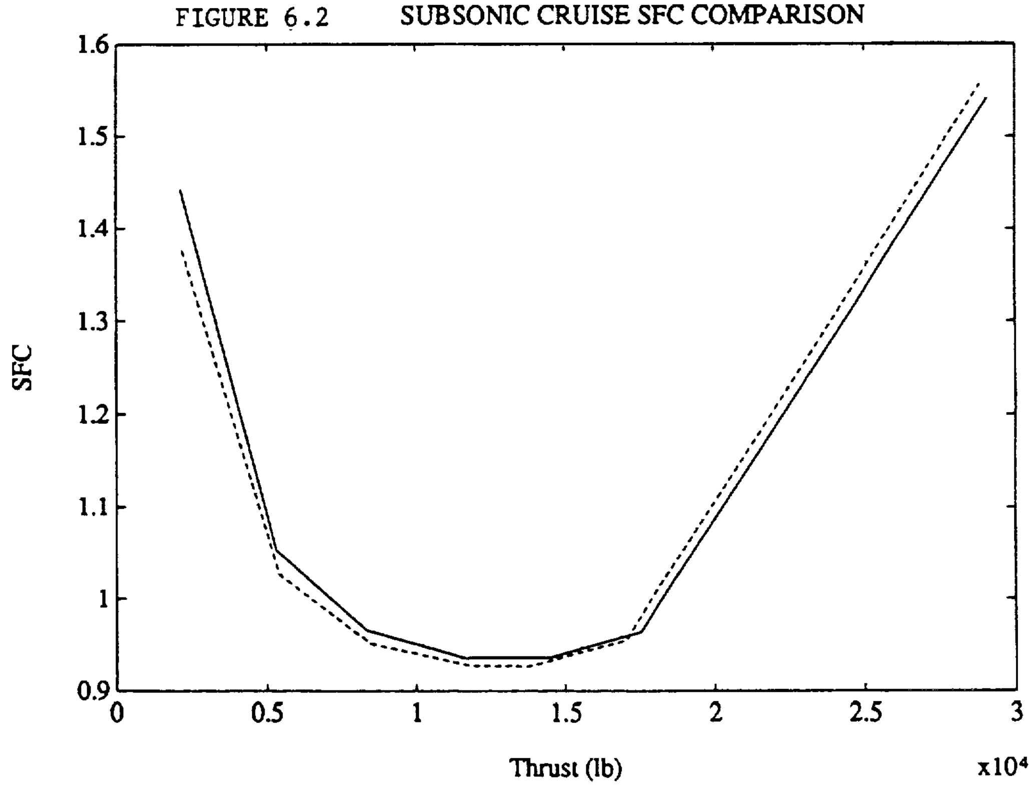


FIGURE 6.2 SUBSONIC CRUISE SFC COMPARISON



	ΔHPT Efficiency (pts)	ΔLPT Efficiency (pts)	% Change in SFC
Supersonic Cruise	0.5	0.24	0.2%
Subsonic Cruise	0.5	0.24	0.3%

Turbine tip clearances are typically of the order of 25 to 30 mls. This figure is reduced to approximately 15mls in present day commercial applications by utilizing active clearance control mechanisms. These mechanisms operate open–loop with no direct measurement of the tip clearance and use simplified calculations of turbine rotor growth, stator growth to determine the desired clearance. The clearance is controlled by modulating turbine cooling flow by means of control valves.
With the use of a direct measurement device such as a clearanceoneter and/or sophisticated analytical models it is projected that tip clearances can be reduced to 5mls with an ultimate goal of 3mls. In this study it was assumed that no active clearance was present and the technology would be available to reduce the clearance from 30mls to 3mls. The required technologies are described in section 6.1.1.

6.1.1 Component Requirements For Active Tip Clearance Control

Two alternative techniques, direct measurement using clearanceometers and secondly an analytical method exist for the implementation of Active Tip Clearance Control to HSCT. The first method will require six (6) turbine tip clearanceometers to be located circumferentially around the turbine case/shroud for each turbine blade row. It has been assumed that the turbines are single stage and counter–rotating. The six clearanceometers are required to accurately measure the minimum tip clearance due to out of roundness and thermal gradients. The logic and associated electronics to determine the minimum turbine tip clearance is located in the FADEC. Low turbine tip clearances may require that active tip clearance concept be integrated with the vehicle weather system to anticipate and avoid rubs when turbulence is encountered.

The casing manifolds are designed to provide good flow distribution (minimize temperature gradients) and it is assumed only cooling is required – no heating of the turbine shroud is required. The cooling flow is controlled by separate HP and LP air valves. The air valves will be located as far forward on the engine as practical to minimize the environmental effects that the valves must tolerate.

The second method to determining tip clearances is the use of a detailed analytical model for the computation of turbine tip clearance. The development of a model capable of providing the required degree of accuracy entails the construction of three distinct models, a heat transfer model, a secondary cooling flow model and also a mechancical design model. Since the model uses as its inputs existing measured engine parameters the only additional hardware requirement is for the FADEC to have sufficient throughput capability and memory capacity. Approximately 50K Bytes of memory will be utilized to support the models required.

The cost, weight and maintenance associated with implementing the two methods of Active Turbine Tip Clearance Control is defined in Table 6.1–1. It should be noted that cooling manifolds and configuration items are not included in the C&A roll–ups.

Table 6.1–1. Concept II: Active Tip Clearance Control using sensors		
Weight:		Total
Air Valve (2)	24.0	
– Actuator w/LVDT		
– Butterfly Valve		
Check Valve	3.0	
Tip Clearance Sensors (12)	11.4	
Delta FADEC	0.8	
		39.2 lbm
Cost:		
Air Valve (2) (3550*2)	$ 7.1K	
Check Valve	$ 0.5K	
Tip Clearance Sensors (12)	$ 5.1K	
Delta FADEC	$ 2.2K	
		$ 14.9K
Maintenance:	MMH	LRU (F/10**6)EFH
Actuator Assembly (16)	0.4	43.1
CVSV Control Module	0.5	250.0

b) Active Tip Clearance Control using Analytical Model		
Weight:		Total
Air Valve (2)	24.0	
–Actuator w/LVDT		
–Butterfly Valve		
Check Valve	3.0	
Delta FADEC	0.8	
		27.8 lbm
Cost:		
Air Valve (2)	$ 7.1K	
Check Valve	$ 0.5K	

Delta FADEC	$ 2.2K	
		$ 9.8K
Maintenance:	MMH	LRU (F/10**6)EFH
Actuator Assembly (16)	0.4	43.1
CVSV Control Module	0.5	250.0

6.1.2 Aircraft Sizing Results

The active turbine tip clearance control concept allowed a reduction of 27 mils out of a total of 30 mils available. A control hardware weight increase of 39 lbs, at scale 1, is required if clearance sensors are used. For a 10 mil reduction in HP tip clearance reductions of 0.2 percent supersonic (2.4) and 0.3 percent subsonic uninstalled SFC were realized. Considering 27 mils then, reductions of 0.54 percent supersonic and 0.81 percent subsonic were used. As seen from Table 8.1 even with a small increase in control system hardware weight, the reduction in SFC is dominant, leading to a 0.9 percent reduction in TOGW. If the analytical approach was used then a reduction of 1.0 percent in TOGW would be realized.

6.1.3 Direct Operating Cost Results

The Active Turbine Tip Clearance concept produced a $404/trip (–0.45%) lower DOC than the baseline due to a 1.22% reduction in fuel burn if cleananceometers are used and a $424/trip if the analytical approach is used. This concept was slightly more expensive than the baseline to manufacture and maintain, however, the impact these had on DOC was negligible as shown in Figure 8.1. Therefore, the total DOC reduction was nearly identical to the delta DOC due to the reduced fuel burn.

6.1.4 Results Summary for ATCC

The improvements to be obtained when using Active Turbine Clearance Control as compared with the baseline are :–

Delta Manufacturing Cost ($/eng)	14.9K
Delta Maintenance ($/EFH)	0.36
Delta Fuel Burn (%)	–1.22
Delta Engine Size (%)	–0.8
1000 Fleet Delta DOC/Year ($ Million)	–307.0

7.0 CONCEPT III: PERFORMANCE IMPROVEMENT

7.1 PERFORMANCE SEEKING CONTROL (PSC)

The difference in performance between a nominal new engine and an actual engine is due to 1) engine–to–engine variatons, either quality and/or deterioration, 2) scheduling errors and compromises, 3) off–nominal operating conditions. This reduction in performance can be partially recovered by the use of an on–line algorithm to fine tune steady–state control schedules. The implementation of the algorithm is shown in Fig 7.1–1 and comprises three elements, an engine model, a performance tracking filter and an optimizer.

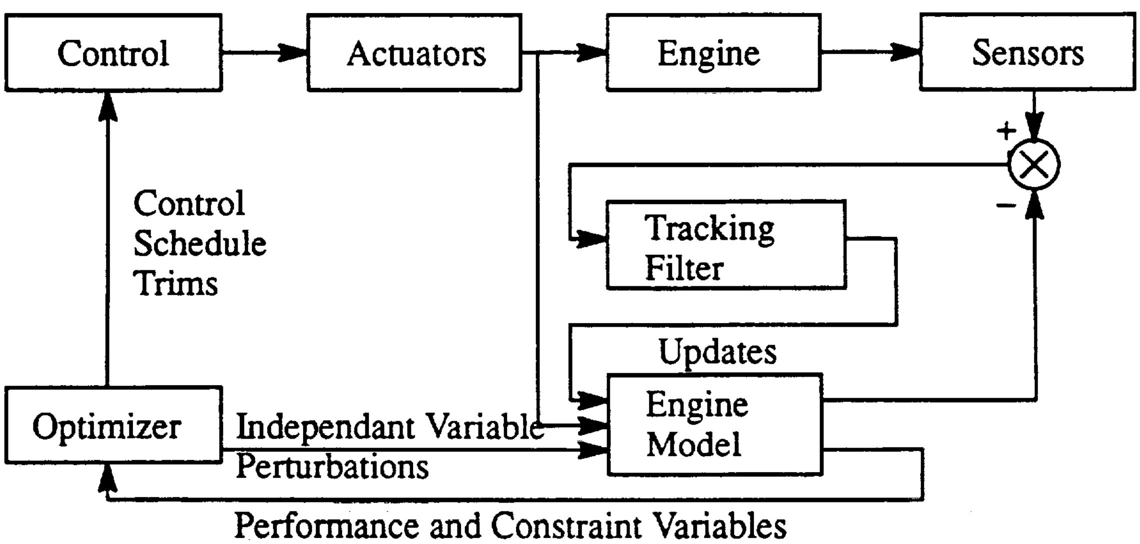


Fig 7.1–1 Performance Seeking Control Concept

The engine model is a low frequency, real–time aerothermodynamic transient model derived from the physics of individual engine components and capable of providing an accurate representation of the performance of a nominal engine. The performance of the actual engine is compared to the nominal engine performance and the differences are used by the optimizer to trim the control schedules by changing reference values observing constraints on stall margins, speeds, temperatures, pressures and other engine operating limits.

Simulation of the performance seeking concept and engine test data indicate that a reduction in SFC of 2% combined with a reduction in temperature margin of 10–30°F is possible for an HSCT application.

7.1.1 Component Requirements for Performance Seeking Control

Implementation of Performance Seeking Control (PSC) concepts to HSCT do not require additional C&A hardware. However, implementation of PSC would require that proposed FADEC (Full Authority Digital Electronic Control) have sufficient throughput capability and memory. Approximately 50K Bytes of memory will be utilized to support the tracking filter and aircraft/engine component level models. The cost associated with the increased memory is defined in Table 7.1–1.

Table 7.1–1 Concept III(a): Performance Seeking Control			
Weight:			Total
None			
Cost:			
Delta FADEC memory		$ 2.2K	
			$ 2.2K
Maintenance:		MMH	SVR (F/10**6)EFH
None			

7.1.2 Aircraft Sizing Results

The performance seeking control concept can provide upto a 2 percent reduction in supersonic (2.4) SFC with no penalty in control system hardware weight. As indicated previously, the HSCT aircraft flying the all supersonic mission is dominated by fuel burn in the Mach 2.4 cruise leg. A 2 percent reduction in supersonic SFC translates into a 2.9 percent reduction in TOGW, see Table 8.1.

7.1.3 Direct Operating Costs

The Performance Seeking Control concept produced a $1496/trip (–1.68%) lower DOC than the baseline and this was the largest DOC reduction of the five concepts studied. A 4.19% fuel burn savings coupled with no maintenance cost and a negligible acquisition cost increase, produced a measurable DOC reduction. As shown in Figure 8.2, the delta DOC due to fuel was again nearly identical to the DOC reduction.

7.1.4 Results Summary for PSC

Delta Manufacturing Cost ($/eng)	2.2K
Delta Maintenance ($/EFH)	0.0
Delta Fuel Burn (%)	–4.19
Delta Engine Size (%)	–2.85
1000 Fleet Delta DOC/Year ($ Million)	–1,136.8

7.2 INTELLIGENT/DIAGNOSTIC CONTROL (IDCS)

The Intelligent/Diagnostic Control concept is designed to utilize the recently developed computational power made available with advanced FADEC's (full authority digital engine control). To enhance engine performance, improve reliability and lower life–cycle cost the concept incorporates PSC described in concept III(a), analytical redundancy failure detection methods developed during the ARTERI program (ref 1) and diagnostic and condition monitioring techniques.

It is projected that the reliability requirement for control system related hardware for an HSCT application will be an order of magnitude greater than the dual processor based architectures used in current civil applications. To achieve the desired degree of reliability improvement without resorting to four processor channels connected in a dual–based architecture, three redundant channels of computation may be used in conjunction with analytical redundancy to detect, isolate and reconfigure soft and hard control system failures to achieve the desired degree of fault tolerance. The failure detection, isolation and corrective action algorithms have been developed during the ARTERI (Analytical Redundancy Technology for Engine Reliability Improvement) program. The ARTERI system design shown in Fig 7.2–1 consists of a detailed real–time component level engine model, a component tracking filter, failure detection and isolation logic and also reconfiguration logic to maintain engine performance as far as possible.

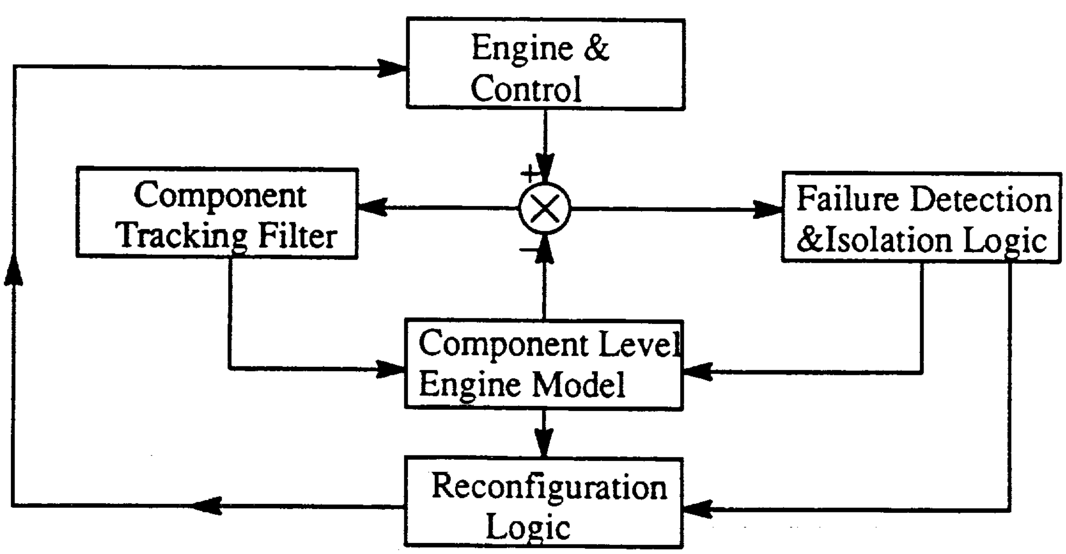


Fig 7.2–1 Arteri Concept

The function of the component tracking filter is to tune the engine model to match the actual engine by updating engine dynamic states, model inputs (actuator positions), model outputs (sensor measurements), and component performance parameters. The failure detection and isolation logic utilizes the estimates of internal engine sensors and actuation sensors predicted by the engine model to identify hard and soft control sytem faults. The reconfiguration logic substitutes model outputs for identified sensor and actuation system failures.

Engine condition monitoring and diagnostic techniques identify and locate failures, and also trends of engine deterioration in use. This contributes to reduced life cycle cost, reduced turnaround time and maintenance costs. Present day commercial applications use ground–based gas path analysis for engine component diagnostic and performance trending. The GE gas analysis program TEMPER, uses engine measurements to estimate engine performance and engine sensor measurements recorded at selected operating conditions for post–flight, off–line analysis to guide maintenace actions.

The failure detection of engine control sensors and actuators utilizing ARTERI combined with the use of a component tracking filter to estimate component flow and efficiency modifiers in real–time corresponds to the information obtained using the on–line gas analysis program. As a result real–time monitoring of the condition of engine components is possible. This allows earlier detection of component failures providing both life–cycle cost and maintenance benefits combined with the ability to reconfigure the control strategy to yield better performance.

7.2.1 Component requirements for Intelligent/Diagnostic Control

In addition to the increased memory and throughput requirement imposed on by PSC on the FADEC, intelligent/diagnostic control also requires additional hardware and memory for ARTERI, condition monitoring

Table 7.2–1 Concept III(b): Intelligent/Diagnostic Control			
Weight:			Total
Delta Fadec & Condition Monitoring Hardware		23.2	
			23.2 lbm
Cost:			
Delta Fadec		$ 32.7K	
			30.0K
Maintenance:		MMH	LRU (F/10**6)EFH
None		0.4	104

7.2.2 Aircraft Sizing Results

The intelligent diagnostic control concept can provide a 2 percent reduction in supersonic SFC. However there is a small control system hardware increase of 23 lbs at scale 1. As shown, supersonic fuel burn being dominant, a reduction of 2.9 percent TOGW can be realized with this control system, see Table 8.1.

7.2.3 Direct Operating Costs

The Intelligent Diagnostic Control concept produced the same fuel burn reduction (–4.19%) as the Performance Seeking concept, however, increased manufacturing and maintenance costs ate into the DOC savings. The DOC was $1304/trip

(–1.46%) lower than the baseline, which makes this the second best concept behind the Performance Seeking Control concept, in terms of DOC savings. As shown in Figure 8.1, the maintenance cost increase along with a slight increase in acquisition cost ate into the delta DOC due to fuel, although a measurable savings still remained. The DOC results quoted have not taken into consideration the significant benefits that will result from improved reliability and life–cycle cost which are inherent when using IDCS. These benefits were not determined since they are beyond the scope of this study.

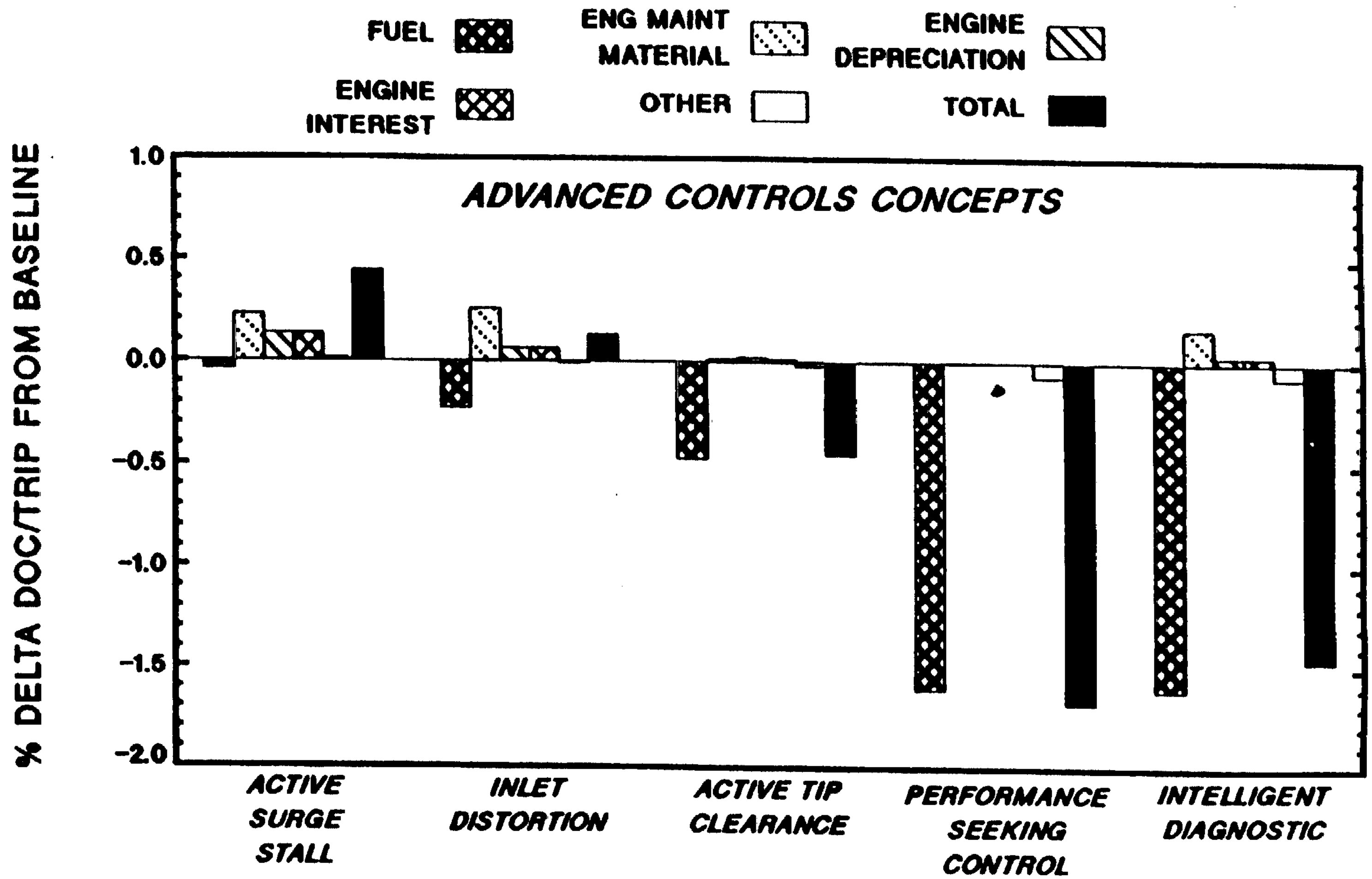
7.2.4 Results Summary for IDCS

The improvements to be obtained as compared to the baseline when using Intelligent Diagnostic Control are :–

Delta Manufacturing Cost ($/eng)	30.00K
Delta Maintenance ($/EFH)	9.09
Delta Fuel Burn (%)	– 4.19
Delta Engine Size (%)	–2.85
1000 Fleet Delta DOC/Year ($ Million)	–991.20

FIGURE 8.1 **BREAKDOWN OF HSCT DOC RESULTS**

12% INTEREST - 1990 DOLLARS - FUEL = $0.65/US GAL - 5000nm - 760 TRIPS/YEAR



	ACTIVE SURGE STALL	INLET DISTORTION	ACTIVE TIP CLEARANCE	PERFORMANCE SEEKING CONTROL	INTELLIGENT DIAGNOSTIC
• DELTA DOC/TRIP ($)	395	113	-404	-1496	-1304
• 500 FLEET DELTA DOC/YEAR ($ MILLION)	150.0	43.0	-153.5	-568.4	-495.6
• 1000 FLEET DELTA DOC/YEAR ($ MILLION)	300.1	85.9	-307.0	-1,136.8	-991.2

8. RESULTS & CONCLUSIONS

In this study the impact on aircraft sizing of each control system concept is investigated through its affect on overall engine system weight and SFC (fuel burn). Approximately 70–75 percent of the overall mission fuel burn for the design, all supersonic 5000nm mission, occurs during the Mach 2.4 leg. As shown by the results of this study, if the control system philosophy impacts only engine system weight, payoffs through reductions in TOGW are small. Viewing the aircraft TOGW as a figure of merit, improvements, ie lower TOGW, will be enhanced if the control philosophy in addition to reducing engine system weight also reduces engine fuel burn during the supersonic leg. From an aircraft sizing perspective, active tip clearance, performance seeking and intelligent diagnostic control concepts show a measurable TOGW reduction over the baseline aircraft and are therefore potential candidates for further study. The results of the study are summarized in Table 8.1.

The above conclusion is confirmed if direct operating costs are considered. Since the fuel usage is the largest piece of the DOC pie, control concepts that produce a significant reduction in fuel burn will improve the DOC of the system. These produced a variation in DOC/trip relative to the baseline of +0.44% to –1.68% as shown in Figure 8.1. When the fuel savings is small (Active Surge/Stall and Inlet Distortion), then the other elements such as maintenance and acquisition costs take on increasing importance. Active Tip Clearance, Performance Seeking and Intelligent Diagnostic concepts produced a measurable DOC savings over the baseline concept. Active Tip Clearance Control, provides a 1.22% reduction in fuel burn (a reduction of $404/trip) compared to a 4.19% reduction in fuel burn for PSC (a reduction of \$1496/trip). This is significant since 4.19% represents the maximum potential reduction in fuel burn offered by PSC, the actual fuel burn is determined by engine–to–engine variations, and the level of engine deteoriaration. As a result the actual value may be less than predicted.

TABLE 8.1 **AIRCRAFT SIZING RESULTS**

CONCEPT	Δ TOGW (%)	Δ OEW (%)	Δ BLOCK FUEL (%)	Δ ENGINE SIZE (%)	Δ CONTROL SYSTEM (lbs/eng)	CONTROL IMPACT ON Δ CRUISE SFC (%)	CONTROL IMPACT ON Δ ENGINE WT (lbs)
BASELINE	BASE	BASE	BASE	BASE	BASE	BASE	BASE
ACTIVE STALL/SURGE	–0.11	–0.11	–0.11	–0.1	185.6	NONE	–204.0
INLET DISTORTION	–0.59	–0.67	–0.60	–0.7	78.2	NONE	–253.5
ACTIVE TIP CLEARANCE	–0.86	–0.54	–1.22	–0.8	46.6	–0.54 SUPERSONIC –0.81 SUBSONIC	NONE
PSC	–2.91	–2.04	–4.19	–2.85	NONE	–2.0	NONE
INTELLIGENT DIAGNOSTIC	–2.90	–2.02	–4.18	–2.85	29.2	–2.0	NONE

* BASELINE NET ENGINE SCALE FACTOR 1.265

9. RECOMMENDATIONS

1. Intelligent/Diagnostic Control & Active Tip Clearance Control

The results of the study indicate that that Intelligent/Diagnostic Control and Active Tip Clearance Control be considered for further development for a High Speed Civil Transport application. The full benefits of Intelligent/Diagnostic Control in terms of Life–cycle cost and improved reliability were beyond the scope of this study and only the Performance Seeking Control benefits have been identified. It is certain that the additional benefits obtained from life–cycle cost and improved reliability will be significant.

For Active Tip Clearance Control two alternative implementation techniques were considered, a sensor measurement method and an analytical method. The analytical approach is preferred since it provides a cost saving of $5.1K combined with a small weight saving and improved reliability.

In addition to the above concepts it is highly recommended that Performance Seeking Control when operating in the Acoustics Mode and also Integrated Inlet/Engine/Nozzle Control strategy be considered for further study. These concepts were not considered during the preliminary screening study for the reasons described below. However the potential benefits that may be realized from these concepts warrant that they should be given serious consideration for any follow–on study. A description of each concept togethor with potential benefits is outlined below.

2. Performance Seeking Control for Acoustics Mode

During preliminary studies, concepts which addressed techniques for reducing engine noise were considered. The inability to implement the concepts due to lack of technology within the timeframe of the the HSCT program prevented their consideration for detailed evaluation. Recent studies at GE Aircraft Engines as part of the Intelligent Engine Control program (ref 4) show that the benefits of Performance Seeking Control can be extended to include the minimization of acoustics while providing rated or other specified thrust at take–off, or maximize thrust for a specified acoustic level, also at take–off. As a result PSC would not only minimize SFC or fuel burn during cruise but provide a means for adapting to changing performance objectives. PSC has been successfully demonstrated on a YF120 engine at Arnold Engineering Development Center in late 1990 and shown to provide a significant improvement in SFC at a single operating point. It is intended to further test and apply PSC technology to a broad range of engine applications at GE.

To perform a PSC feasibility and evaluation study for the HSCT the following steps will be required:

1. Develop model of the HSCT propulsion system for use as a real–time model embedded in the digital control.
2. Design a tracking filter to tune the model to the actual engine. The tracking filter ensures that the errors in the estimates of performance variables (thrust, acoustic parameter, turbine temperature, stall margins, airflow, and SFC) are minimized.
3. Integrate the propulsion system model and tracking filter with existing PSC optimizer.
4. Evaluate benefits of PSC for improvements in:
   a) Acoustics
   b) Fuel consumption

5. Estimate the benefits of extending PSC for:

a) Engine + Inlet + Nozzle

b) Overall HSCT system (Airframe + Engine + Inlet + Nozzle)

c) Special cases (re–optimize control schedules for failed actuators, etc.)

4. Integrated Inlet/Engine/Nozzle Control Strategy

The study of an integrated inlet/engine/nozzle control strategy was considered to be outside the scope of this particular program. However the expected benefits are large enough that the concept shuld not be ignored for a follow–on study. The economic viability of the High Speed Civil Transport (HSCT) is directly related to the performance of the propulsion device, that is, the inlet/engine/nozzle system. The HSCT will cruise at Mach 2.4 and consequently require a mixed–compression inlet to maximize overall propulsive efficiency. With internal compression, the performance (steady–state and dynamic stability) of the inlet and engine becomes highly coupled and thus requires an integrated design effort.

The mixed–compression inlet must be stable and resistant to unstarts in the face of both external (ex. angle of attack variation) and internal (ex. engine power change) disturbances. One way to improve inlet stability is to nominally position the terminal normal shock downstream of the inlet throat. However, as the shock moves downstream of the throat and closer to the engine face, performance (ie. recovery) is degraded and inlet distortion increases. Therefore, the system must maintain stable operation with the terminal normal shock at or near the inlet throat. The most effective means of accomplishing this is with an integrated strategy which controls all of the engine and nozzle variable geometry in addition to the inlet variable geometry and bypass and stability bleed flows. The main benefit of this strategy is improved inlet recovery while maintaining acceptable stability. Preliminary studies show a 1% change in inlet recovery for an HSCT will provide a 1.5% reduction in TOGW.

While an integrated control will minimize the occurence, inlet unstarts may still happen (in response to an engine stall for example). Coordinated inlet/engine restart logic can be included as part of the integrated control strategy.

GE's approach to this problem is to combine the analysis techniques for simulating the transient behavior of both the supersonic mixed–compression inlet and the engine. A generic inlet model LAPIN (large amplitude perturbation inlet) which includes large flow field perturbatations like hammershock, unstart/restart, bleed, bypass, and geometry effects will be used to construct an inlet model for the HSCT engine. The model will include in–stall characteristics (critical to restart logic) and volume dynamics. The inlet model will be integrated with engine and nozzle simulations to enable the overall system dynamic behaviour to be studied. This approach was utilized by GE on the National Aerospace Plane (NASP) program.

10. REFERENCES

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APPENDIX

PHASE I – FINAL REPORT

CONTRACT NAS3-25460

TASK ORDER NO. 6

ADVANCED CONTROL FOR AIRBREATHING ENGINES

FINAL REPORT FOR PERIOD
JANUARY 1990 TO AUGUST 1990

SEPTEMBER 1990

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ADVANCED CONTROL FOR AIRBREATHING ENGINES

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ADVANCED CONTROL FOR AIRBREATHING ENGINES

NOMENCLATURE

ABRS	Active Afterburner Rumble Suppression
ANS	Active Jet Noise Suppression
BPF	Active Burner Pattern Factor Control
CHGS	Active Combustor Howl/Growl Suppression
CIDC	Active Compressor Inlet Distortion Control
FOM	Figure of Merit
HPMF	High Performance Military Fighter
HSCT	High Speed Civil Transport
IDCS	Intelligent Diagnostic/Control Sysyem
PSMC	Performance Seeking Control
SCAC	Secondary Cooling Airflow Control
SSC	Active Stall/Surge Control
TCC	Active Tip Clearance Control
VCE	Variable Cycle Engine

ADVANCED CONTROL FOR AIRBREATHING ENGINES

1.0 SUMMARY

A preliminary screening of advanced control features/concepts for airbreathing engines was performed to enable further detailed studies on the more promising concepts. Descriptions and block diagrams were developed for ten advanced control concepts which could impact turbine engine performance and operability in High Speed Civil Transport and High Performance Military Fighter applications. Figures of Merit were developed to measure the impact of each concept on performance, operability, control complexity, and life cycle cost. The overall results were used to rank the concepts in order of desirability for further study.

ADVANCED CONTROL FOR AIRBREATHING ENGINES

2.0 INTRODUCTION

Application of Advanced Controls to Airbreathing Engines offers potential for improvement of performance and operability. Detailed studies are planned as part of the Advanced Propulsion Concepts (APC) program, to provide detailed quantified measures of such improvement for various engine control features as applied to several aircraft types (specifically, Military High Performance Fighter and High Speed Civil Transport). The purpose of this study is to perform a preliminary screening on the usefulness of various control features/approaches/concepts to enable further detailed studies.

3.0 DISCUSSION

3.1 Subtask 1 - ESTABLISH CONTROL CONCEPTS

Ten control concepts which could impact turbine engine performance and operability were selected for consideration.

- Active Burner Pattern Factor Control
- Active Tip Clearance Control
- Active Compressor Inlet Distortion Control
- Active Jet Noise Suppression
- Active Surge/Stall Control
- Performance Seeking Control
- Intelligent Diagnostic/Control Systems
- Secondary Cooling Airflow Control
- Active Combustor Howl/Growl Control
- Active Afterburner Rumble Suppression

A schematic block diagram and detailed description of each concept with effects on performance, operability, control complexity, and life cycle cost is included in the Appendix. The following material briefly describes the objective of the concepts.

1) Active Burner Pattern Factor Control - This concept senses and controls hot streaks by modulating fuel flow from combustor injectors. The objective is to operate at higher average maximum temperature without reducing hot parts life.

2) Active Tip Clearance Control - This concept senses clearances and modulates cooling/heating airflow to turbine casings to control clearances, thus improving HP and LP turbine performance and life.

3) Active Compressor Inlet Distortion Control - This concept computes inlet distortion and controls sectors of variable compressor vanes to dissipate the effect on stall margin. The objective is to reduce stall margin requirements and operate stall free with distortion.

4) Active Jet Noise Suppression - This concept senses near-field pressure oscillations, amplifies the error from a preset threshold, and uses acoustic drivers to inject a high frequency tone into the turbulent jet in the engine tailpipe to reduce jet emission noise.

5) Active Surge/Stall Control - This concept senses a stall precursor and suppresses instability by controlling sectors of variable vanes or modulating bleeds, fuel flow and stator vanes. The objective is to be able to operate compressors in the stall region.

6) Performance Seeking Control - This concept optimizes predetermined schedules by using an embedded engine model and a gradient optimization module to: improve SFC at thrust; or improve temperature margin at thrust; or maximize thrust at temperature.

7) Intelligent Diagnostic/Control System - This approach optimizes schedules like Performance Seeking Control and adds capabilities to monitor the health of the engine and control system, to accommodate faults/damage in the engine and control system, including reconfiguration of the control when necessary. The objective of these features is to optimize performance, improve IFSR and mission completion.

8) Secondary Cooling Airflow Control - HP and LP turbine blade temperatures are sensed and cooling air is modulated to control blade temperature. SFC is improved by reducing cooling flow for off-design operation.

9) Active Combustor Howl/Growl Suppression - This feature senses pressure oscillations and modulates main combustor fuel flow to suppress combustion instabilities. The payoff is reduced noise and increased main combustor life.

10) Active Afterburner Rumble Suppression - This concept senses pressure oscillations and modulates afterburner fuel flow to suppress combustion instabilities. Noise and afterburner liner weight are reduced while afterburner life is increased.

Certain company highly proprietary concepts were not included in this list. Model Based Control was excluded as well as some approaches on Active Tip Clearance Control.

3.2 Subtask 2 - ESTABLISH BASIS OF COMPARISON

Two reference aircraft/engine combinations (a High Speed Civil Transport and High Performance Military Fighter) were selected for use as a basis for comparative evaluation of the control concepts. The missions for these advanced VCE engine powered aircraft are shown on Figures 3.2-1 and 3.2-2.

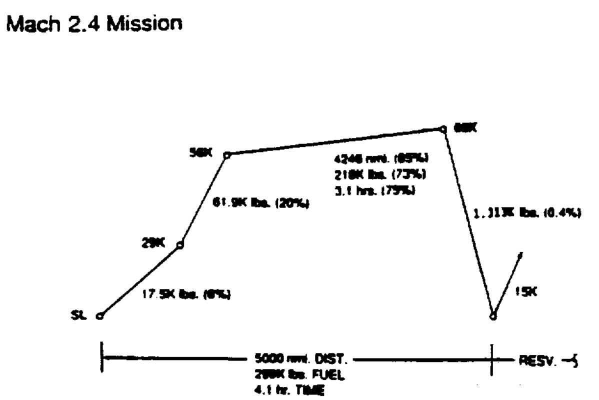

FIGURE 3.2-1: HSCT MACH 2.4 MISSION

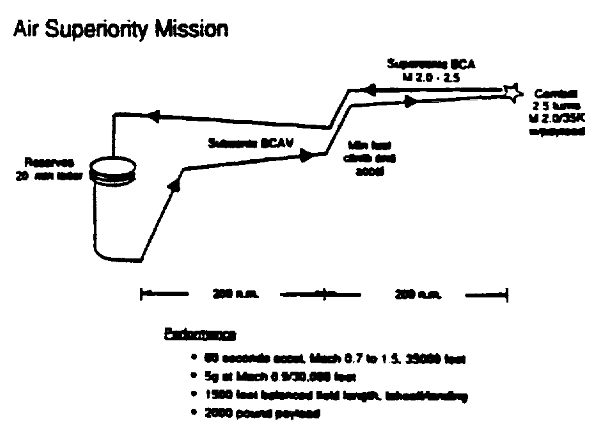

FIGURE 3.2-2: HPMF AIR SUPERIORITY MISSION

Twelve engineers from Performance, Preliminary Design, Advanced Systems Analysis, and Controls organizations provided opinions on the relative importance of the four major categories of performance, operability, control complexity, and life cycle cost.The results, designated as PR, are shown in Figure 3.2-3. They also participated in the selection and weighting of the subcategory criteria associated with the major categories, designated as In,i. These results are shown on Figure 3.2-4. Average values were determined for use in the Figure of Merit calculations by deleting high and low numbers. A group of four Controls engineers and six Preliminary Design/Advanced Systems Analysis engineers then estimated the contribution of each candidate control concept with respect to each subcategory item (designated ai,j). Finally, a Figure of Merit was determined for each candidate control concept using the following formula:

$$FM_j = PR_1\left(\sum_{i=1}^{n_1} I_{1,i}a_{1,i}\right) + PR_2\left(\sum_{i=1}^{n_2} I_{2,i}a_{2,i}\right) + PR_3\left(\sum_{i=1}^{n_3} I_{3,i}a_{3,i}\right) + PR_4\left(\sum_{i=1}^{n_4} I_{4,i}a_{4,i}\right)$$

where

FM_j	=	Figure of Merit (overall) for control concept (j)	
PR_n	=	Relative importance of 4 major categories	range: 1-10
$I_{n,i}$	=	Relative ranking of element (i) of major category (n)	range: $\sum_{i=1}^{n} I_{n,i} = 1.0$
$a_{i,j}$	=	Contribution to element (i) of control concept (j).	range: 0-10

Figures 3.2-5 and 3.2-6 illustrate the resulting Figures of Merit for the High Speed Civil Transport and High Performance Military Fighter respectively.

HIGH SPEED CIVIL TRANSPORT

CRITERIA	Engineer 1	2	3	4	5	6	7	8	9	10	11	12	sum	adj sum	avg
Performance	6	5	4	9	10	10	7	9	10	9	5	8	92	78	7.80
Operability	5	8	6	5	5	3	10	8	8	3	7	10	78	65	6.50
Complexity	8	10	8	7	7	3	5	10	7	3	9	6	83	70	7.00
LCC	10	10	9	10	8	8	4	10	9	10	10	4	102	88	8.80

MILITARY HIGH PERFORMANCE FIGHTER

CRITERIA	Engineer 1	2	3	4	5	6	7	8	9	10	11	12	sum	adj sum	avg
Performance	10	10	8	10	8	9	8	10	10	9	9	9	110	92	9.20
Operability	9	10	9	9	10	10	10	9	8	10	7	8	109	92	9.20
Complexity	7	5	6	8	7	4	3	8	8	8	8	5	77	66	6.60
LCC	4	5	4	5	7	5	1	5	7	8	10	7	68	57	5.70

FIGURE 3.2-3: RELATIVE IMPORTANCE OF CRITERIA (PR)

HIGH SPEED CIVIL TRANSPORT

CRITERIA	1	2	3	4	5	6	7	8	9	10	11	sum	adj sum	avg
						Engineer								
sfc/fuel burn	.40	.20	.40	.40	.25	.40	.40	.20	.20	.40	.40	3.65	3.05	.34
temperature	.10	.20	.15	.20	.25	.10	.10	.40	.20	.10	.00	1.80	1.40	.16
thrust/weight	.20	.30	.10	.20	.25	.25	.10	.10	.20	.10	.20	2.00	1.60	.18
noise	.30	.30	.35	.20	.25	.25	.40	.20	.40	.40	.40	3.45	2.85	.32
starting	.30	.20	.30	.30	.10	.15	.40	.50	.20	.50	.50	3.45	2.85	.32
burst	.20	.20	.25	.30	.25	.25	.30	.00	.20	.10	.20	2.25	1.95	.22
chop	.20	.20	.15	.10	.15	.20	.10	.10	.20	.10	.20	1.70	1.60	.18
ab lo	.15	.20	.20	.10	.25	.30	.10	.30	.20	.20	.10	2.10	1.70	.19
maneuvering	.15	.20	.10	.20	.25	.10	.10	.10	.20	.10	.00	1.50	1.25	.14
failure rate	.55	.55	.55	.50	.70	.70	.50	.70	.50	.40	.20	5.85	4.95	.55
maintenance rate	.45	.45	.45	.50	.30	.30	.50	.30	.50	.60	.80	5.15	4.05	.45
development cost	.20	.20	.15	.10	.20	.20	.10	.10	.10	.10	.10	1.55	1.25	.14
acquisition cost	.20	.20	.25	.20	.30	.20	.30	.30	.30	.10	.10	2.45	2.05	.23
operating cost	.30	.30	.30	.30	.10	.35	.30	.30	.30	.40	.40	3.35	2.85	.32
maintenance cost	.30	.30	.30	.40	.40	.25	.30	.30	.30	.40	.40	3.65	3.00	.33

MILITARY HIGH PERFORMANCE FIGHTER

CRITERIA	1	2	3	4	5	6	7	8	9	10	11	sum	adj sum	avg
						Engineer								
sfc/fuel burn	.30	.20	.15	.30	.20	.35	.20	.20	.30	.30	.40	2.90	2.35	.26
temperature	.15	.20	.35	.10	.30	.20	.40	.40	.30	.20	.10	2.70	2.20	.24
thrust/weight	.40	.30	.40	.50	.40	.35	.40	.30	.40	.40	.45	4.30	3.50	.39
noise	.15	.30	.10	.10	.10	.10	.00	.10	.00	.10	.05	1.10	.80	.09
starting	.15	.20	.20	.10	.10	.10	.10	.10	.20	.20	.15	1.60	1.30	.14
burst	.25	.20	.20	.20	.25	.20	.20	.20	.20	.20	.30	2.40	1.90	.21
chop	.20	.20	.20	.20	.15	.20	.10	.20	.20	.20	.05	1.90	1.65	.18
ab lo	.15	.20	.15	.10	.25	.20	.30	.20	.20	.20	.20	2.15	1.75	.19
maneuvering	.25	.20	.25	.40	.25	.30	.30	.40	.20	.20	.30	3.05	2.45	.27
failure rate	.70	.50	.60	.50	.70	.70	.50	.60	.70	.50	.70	6.70	5.50	.61
maintenance rate	.30	.50	.40	.50	.30	.30	.50	.40	.30	.50	.30	4.30	3.50	.39
development cost	.20	.20	.30	.20	.20	.20	.10	.20	.30	.10	.10	2.10	1.70	.19
acquisition cost	.20	.20	.30	.20	.30	.25	.40	.40	.30	.10	.20	2.85	2.35	.26
operating cost	.30	.30	.15	.30	.10	.30	.20	.20	.10	.40	.40	2.75	2.25	.25
maintenance cost	.30	.30	.25	.30	.40	.25	.30	.20	.30	.40	.30	3.30	2.70	.30

FIGURE 3.2-4: SUBCATEGORY WEIGHTING (In,i)

	PR	I	BPF	TCC	CIDC	ANS	SSC	PSMC	IDCS	SCAC	CHGS	ABRS
			Control Concept									
Performance	7.8											
sfc/fuel burn		.34	6.10	8.20	3.80	4.80	4.60	7.00	6.30	7.60	1.50	1.60
temperature		.16	6.70	5.70	2.40	2.30	3.40	6.70	6.00	4.80	.80	.90
thrust/weight		.18	6.20	4.00	4.30	4.70	6.00	4.10	3.50	2.20	2.00	3.60
noise		.32	.60	.70	.70	9.20	.40	1.70	1.80	.30	6.10	4.50
Performance FOM			34.74	36.23	20.86	45.16	25.87	36.92	33.60	29.98	23.00	21.67
Operability	6.5											
starting		.32	2.70	1.90	1.70	.50	3.10	2.30	1.60	1.60	1.90	.30
throttle burst		.22	2.60	3.20	4.20	.60	6.20	2.00	1.70	3.30	1.00	1.30
throttle chop		.18	2.10	3.00	3.00	.50	3.40	2.00	1.60	2.60	1.00	1.20
AB lightoff		.19	1.20	.70	2.10	.70	3.80	1.90	1.70	.80	.40	3.70
maneuvering		.14	1.10	2.10	6.30	.70	6.10	3.00	2.70	1.30	1.00	1.20
Operability FOM			14.27	14.82	21.36	3.98	29.54	15.06	12.19	13.26	7.96	9.55
Control Complexity	7.0											
failure rate		.55	3.10	4.80	4.90	3.40	3.60	7.30	6.40	5.20	5.00	5.60
maintenance rate		.45	3.20	4.80	5.10	3.60	3.60	7.30	6.20	5.20	5.00	5.50
Control Complexity FOM			22.01	33.60	34.93	24.42	25.20	51.09	44.18	36.41	34.99	38.88
Life Cycle Cost	8.8											
development cost		.14	3.70	5.00	4.10	3.50	3.80	5.60	5.10	5.00	4.50	4.50
acquisition cost		.23	3.70	5.20	4.30	3.70	4.30	6.50	5.70	5.20	4.60	4.80
operating cost		.32	5.80	6.80	5.30	3.50	5.50	7.40	7.40	6.50	4.20	4.10
maintenance cost		.33	3.60	5.00	4.20	3.20	4.20	6.60	7.40	4.70	4.70	4.80
Life Cycle Cost FOM			38.84	50.36	40.87	30.95	41.07	60.07	60.15	48.64	40.33	40.74
Overall FOM			110	135	118	105	122	163	150	128	106	111

FIGURE 3.2-5: FIGURES OF MERIT - HSCT

	PR	I	BPF	TCC	CIDC	ANS	SSC	PSMC	IDCS	SCAC	CHGS	ABRS
			Control Concept									
Performance	9.2											
sfc/fuel burn		.26	6.10	7.20	4.30	.70	4.50	7.00	6.60	6.20	1.10	1.20
temperature		.24	7.00	5.30	3.60	.70	3.70	6.20	6.60	4.80	1.10	1.10
thrust/weight		.39	6.50	3.40	5.60	1.30	7.20	4.40	3.60	2.80	2.60	4.20
noise		.09	.40	.60	.40	6.50	.40	1.10	.30	.30	4.70	5.70
Performance FOM			53.71	41.61	38.66	13.28	45.12	47.13	43.53	35.73	18.28	25.08
Operability	9.2											
starting		.14	1.90	1.80	1.80	.70	3.60	2.20	1.90	1.50	2.00	.30
throttle burst		.21	3.20	3.40	4.80	.70	7.20	3.00	2.50	3.40	1.00	1.50
throttle chop		.18	1.80	3.30	3.40	.70	3.50	2.50	1.90	2.70	1.00	1.10
AB lightoff		.19	1.40	.50	3.30	.70	5.20	3.60	2.40	.80	.40	4.20
maneuvering		.27	2.80	3.30	8.80	.70	8.80	4.90	4.80	1.50	.40	1.10
Operability FOM			21.02	23.42	44.85	6.39	55.30	31.24	26.55	18.10	7.87	15.17
Control Complexity	6.6											
failure rate		.61	3.00	4.60	4.60	3.20	3.40	6.80	6.20	5.20	4.90	4.90
maintenance rate		.39	2.70	4.70	4.60	3.40	3.40	6.80	6.10	5.20	4.90	4.90
Control Complexity FOM			19.04	30.62	30.35	21.64	22.45	44.88	40.67	34.33	32.34	32.35
Life Cycle Cost	5.7											
development cost		.19	3.50	4.50	3.90	2.90	3.30	5.40	4.90	4.50	4.40	4.30
acquisition cost		.26	3.70	4.80	4.20	2.80	3.70	6.30	5.50	5.10	4.50	4.50
operating cost		.25	5.30	6.00	5.20	2.90	4.60	7.00	6.60	5.90	4.10	4.00
maintenance cost		.30	3.30	4.50	3.80	3.10	3.70	6.50	7.20	4.50	4.90	5.10
Life Cycle Cost FOM			22.46	28.23	24.36	16.72	21.94	36.26	35.18	28.53	25.65	25.74
Overall FOM			116	124	138	58	145	160	146	117	84	98

FIGURE 3.2-6: FIGURES OF MERIT - HPMF

3.3 Subtask 3 - SCREENING OF CONTROL FEATURES

The advanced control concepts Figures of Merit and rankings from a performance, operability, control complexity, life cycle cost, and overall standpoint are summarized in Figure 3.3-1. Concepts with a high Figure of Merit numerical value are the candidates judged most likely to offer improvement in engine/aircraft operation. Thus the concept with the highest Figure of Merit value is ranked number 1 and the lowest is ranked number 10.

CONTROL CONCEPT	OVERALL FOM		PERFORMANCE FOM		OPERABILITY FOM		COMPLEXITY FOM		LCC FOM	
	HPMF	HSCT	HPMF	HSCT	HPMF	HSCT	HPMF	HSCT	HPMF	HSCT
PSMC	160	163	47	37	31	15	45	51	36	60
IDCS	146	150	44	34	27	12	41	44	35	60
TCC	124	135	42	36	23	15	31	34	28	50
SCAC	117	128	36	30	18	13	34	36	29	49
SSC	145	122	45	26	55	30	22	25	22	41
CIDC	138	118	39	21	45	21	30	35	24	41
ABRS	98	111	25	22	15	10	32	39	26	41
BPF	116	110	54	35	21	14	19	22	22	39
CHGS	84	106	18	23	8	8	32	35	26	40
ANS	58	105	13	45	6	4	22	24	17	31

CONTROL CONCEPT	OVERALL RANKING		PERFORMANCE RANKING		OPERABILITY RANKING		COMPLEXITY RANKING		LCC RANKING	
	HPMF	HSCT	HPMF	HSCT	HPMF	HSCT	HPMF	HSCT	HPMF	HSCT
PSMC	1	1	2	2	3	3	1	1	1	1
IDCS	2	2	4	5	4	7	2	2	2	1
TCC	5	3	5	3	5	3	6	7	4	3
SCAC	6	4	7	6	7	6	3	4	3	4
SSC	3	5	3	7	1	1	8	8	8	5
CIDC	4	6	6	10	2	2	7	5	7	5
ABRS	8	7	8	9	8	8	4	3	5	5
BPF	7	8	1	4	6	5	10	10	8	9
CHGS	9	9	9	8	9	9	4	5	5	8
ANS	10	10	10	1	10	10	8	9	10	10

FIGURE 3.3-1: CONTROL CONCEPT RANKING

4.0 CONCLUSIONS

The ranking of control concepts as shown in Figure 3.3-1 may be conviently divided into two groups (a high ranking top six and lower ranking bottom four). The six concepts in the higher score category are:

Performance Seeking Control (PSMC)
Intelligent Diagnostic/Control System (IDCS)
Tip Clearance Control (TCC)
Secondary Cooling Airflow Control (SCAC)
Active Stall/Surge Control (SSC)
Active Compressor Inlet Distortion Control (CIDC)

These concepts scored in the top six group whether one considered either the High Performance Military Fighter or High Speed Civil Transport. Since the PSMC concepts are also included in IDCS, only five concepts will be considered. These concepts scored higher because they were either less complex to implement, or contributed to several major categories in the ranking or both.

The acoustic concepts did not rank high overall because noise was only a part of one of the four categories, performance. The concepts would have achieved a higher ranking if they scored significantly in the other categories. In the case of active jet noise control, the potential complexity of the concept reduced its overall score, even though the concept could have a major beneficial impact on the engine sizing and operation for the High Speed Civil Transport.

The funding level available for Phase II of this Task Order limits the number of concepts that can be studied. Assuming that control complexity can be brought to a reasonable level by further study of the enabling technologies, the top three candidates considered for each application are:

HSCT	HPMF
IDCS	SSC
TCC	CIDC
SSC	IDCS

5.0 RECOMMENDATIONS

It is recommended that one mission or application be selected and that two control concepts be studied. For each application the following are the recommended concepts in the order of selection.

	HSCT	HPMF
1.	IDCS (short term)	IDCS (short term)
2.	TCC (short term)	CIDC (short term)
3.	SSC (long term)	SSC (long term)

For High Speed Civil Transport, IDCS appears to capture the advantages of diagnostics, performance seeking by software logic, and reconfiguration when control and engine components fail or deteriorate in performance. Enabling technologies to be studied for this concept include reconfiguration control, engine component failure detection and isolation strategies, and high-fidelity real-time engine models.

Active stall/surge control will be very beneficial but very complex and is therefore suited for a long term application. For HSCT applications, TCC will yield benefits in the short term and is being recommended. Technology development needed for TCC includes futher refinement of clearance probe design and associated interface electronics with the digital engine control. A more research oriented alternative will be the active stall/surge control.

For High Performance Military Fighter applications, IDCS again appears to have the advantages discussed earlier for HSCT.

Two concepts, CIDC and SSC meet the operability objectives best but it takes components and subsystems that are quite different to implement the two concepts. CIDC is a concept that can be implemented in the near term because it is relatively less complex. The enabling technologies are a high fidelity engine model which predicts stall margins accurately and hardware/software for a compressor variable-vane sector control. SSC can better meet the operability objectives because it can suppress instabilities during surge and rotating stall. The enabling technologies however are more challenging and can only be considered for implementation in the long term.

Active jet noise control was left out of the recommendations for further study because the concept described has not been researched enough to show viability for jet engine applications. Further IR&D studies are required to reach a viability conclusion.

6.0 APPENDIX

ACTIVE STALL/SURGE CONTROL

Concept

Two types of stall phenomena occur, surge and rotating stall. Surge is the stoppage or reversal of flow in the compression system due to the response of the entire engine. During a surge, the compressor unloads itself by allowing compressed fluid to expand in the upstream direction causing a somewhat planar pressure wave to travel in the reverse direction. A rotating stall is an aerodynamic instability characterized as a local blockage to the axial flow within a compression component which rotates circumferentially in the direction of the rotor rotation at a rotational speed equal to approximately one-half of the rotor speed. The wave frequency for a surge and rotating stall may get as high as 20 and 125 hertz, respectively.

It has been shown in a few isolated cases that the stability limit of an axial-flow compressor can be extended by actively controlling stall/surge. Epstein/Greitzer's studies were conducted on a single-stage, low-speed, 0.5 meter diameter research compressor. This is encouraging, but it is still a large technological leap to apply active stall/surge control to a high-speed, multistage, large-diameter compressor in an engine. There are many questions yet unanswered: What is the precursor to stall? At what stage does stall/surge originate? What is(are) the best location(s) to measure the precursor? Can the engine disturbances be sufficiently filtered to accurately measure the precursor? If the precursor to stall can be identified and then measured by pressure sensors, a possible control methodology to actively control stall/surge would be as shown in Figures 1-A and 2-A.

Figure 1-A shows the global stall/surge control concept, which might be able to control both the surge and rotating stall. An additional control concept may be necessary to ensure the controllability of a rotating stall. As illustrated by Figure 1-A - once a pressure disturbance is measured - high frequency pressure waves are generated by modulating bleeds, fuel flow, and stator vanes, and are applied to the fan and compressor to cancel out stall/surge disturbances at their inception. To actively control rotating stall, variable vanes are linked into n number of sections that are independently controlled. This allows the compressor to act upon the localized blockage. As shown in Figure 2-A, high-frequency pressure transducers measure the rotating pressure-disturbance profile. The active control then computes the magnitude and velocity of the pressure disturbance. A delta vane position for each section is calculated and added to the nominal vane schedule to unload the compressor and eliminate the local separation. Active control of stall/surge permits stable operation with reduced design stall margin requirements.

Effect on Performance

- o Specific thrust can be increased by raising the operating line.
- o SFC is lowered with improved compressor efficiency.
- o Increased design operating line can be traded off for reduced weight by eliminating a compressor stage.

Effect on Operability

- o Restores stable operation upon encountering the onset of compressor/fan instability, thereby, permitting operation with significantly reduced level of stall margin.

Effect on Life Cycle Costs

- o Increases control weight and complexity due to additional pressure sensors, actuators, and linkages.

Effect on Control Complexity

- o Need fast-response pressure sensors.
- o Increased FADEC computational power, speed, and memory. The rotating-stall control update time must be about 1 msec.
- o High frequency actuators for stators, bleeds, and fuel flow valve. Linkages/hardware for independently controlled variable vane sections.

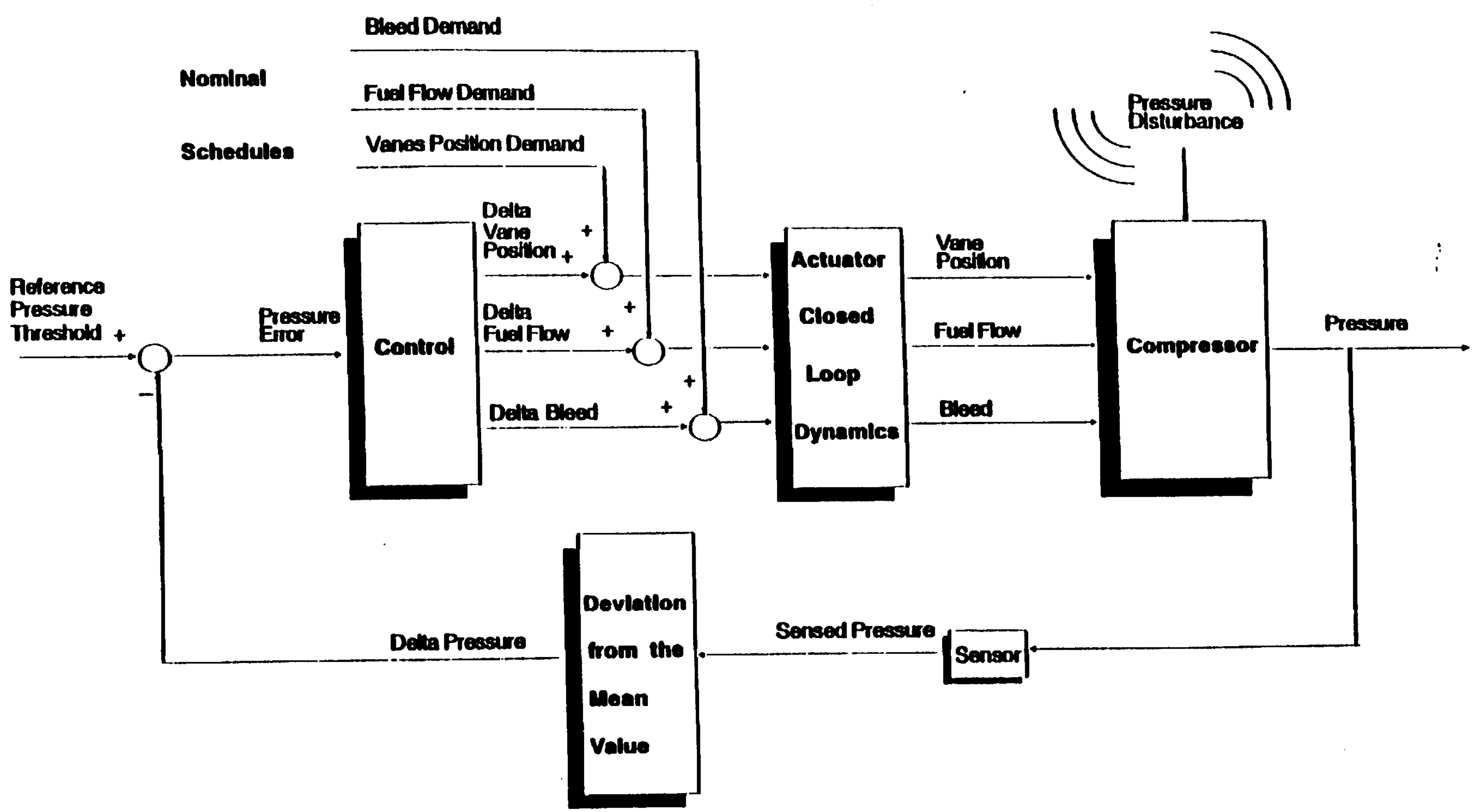

FIGURE 1-A: GLOBAL STALL/SURGE CONTROL

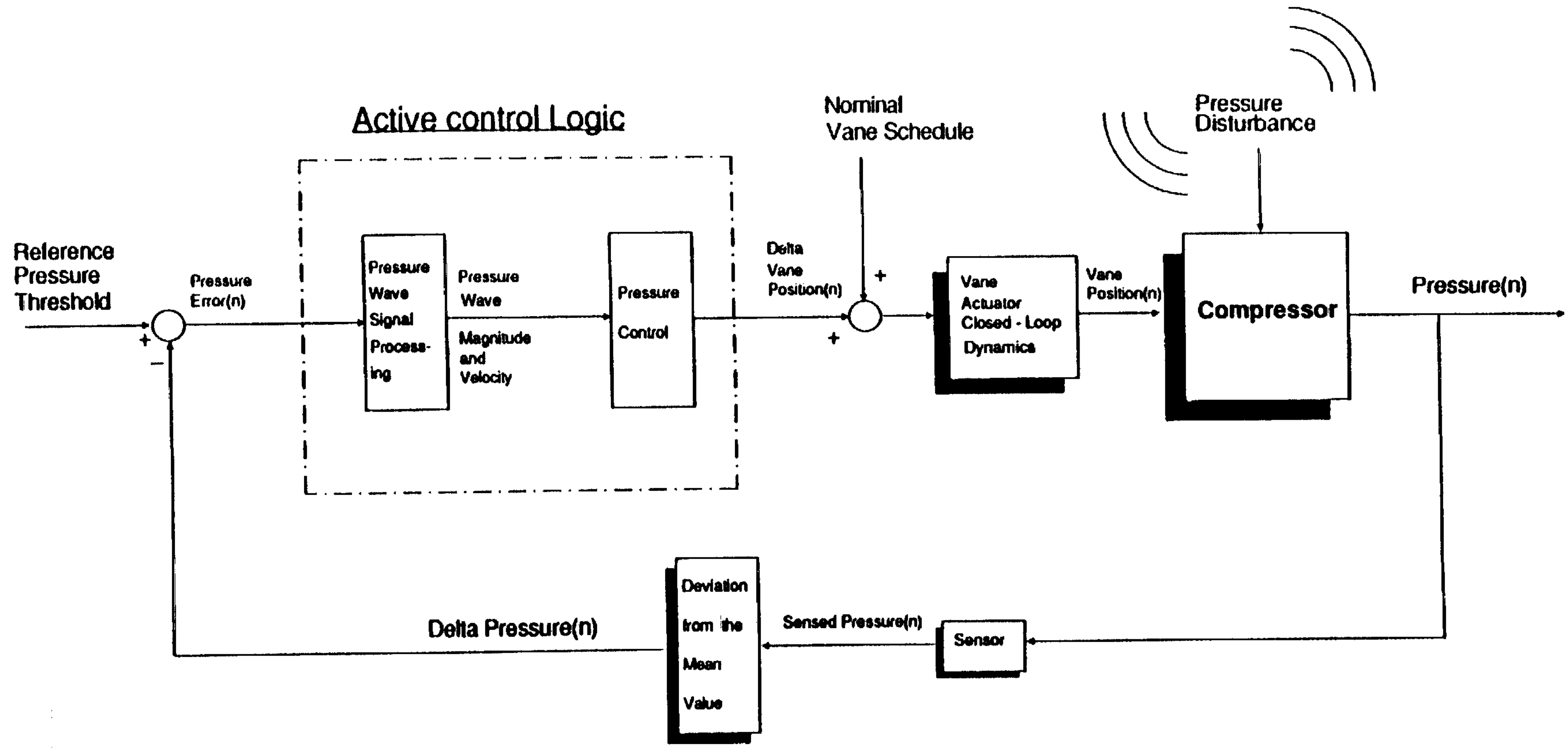

FIGURE 2-A: ACTIVE CONTROL FOR ROTATING STALL

ACTIVE COMPRESSOR INLET DISTORTION CONTROL

Concept

An accurate representation of inlet distortion can be computed by implementing the aircraft's inlet characteristics data in the propulsion digital control. Then, independently controlled variable vane sectors for the fan and compressor are used to dissipate the effect of distortion on stall margin. This process will allow the engine to operate without stall throughout an extended range of inlet distortions. Design stall margin requirements could be reduced, allowing a higher design operating line. Alternatively, the compressor/fan can be redesigned to take advantage of the reduced stall margin requirements resulting from active inlet distortion control. Redesign would allow reduced rotor speed, reduced weight, and increased compressor/fan efficiency.

As shown in Figure 3-A, the control uses engine airflow, flight Mach number, angle of attack, and side-slip angle to calculate the circumferential inlet distortion (IDC). IDC is a measurement of the magnitude of distortion around the face of the fan. Using IDC along with the angle of attack, side-slip angle, and the stall margin deviation, the distortion control logic computes a delta vane position for the fan and compressor sector(s) to be added to the nominal vane schedule. This added delta vane position will reduce the effect of inlet distortion and provide additional fan/compressor stall protection.

Effect on Performance

- Some effect on SFC due to improved compressor efficiency.
- Specific thrust can be increased due to the higher operating line.
- Increased design operating line can be traded off for reduced weight by eliminating a compressor stage.

Effect on Operability

- By expanding the stall margin, engine operability is enhanced allowing aircraft operation over an extended maneuvering envelope.
- Engine operation free from stall/surge during high level of distortion typical for low-observable aircraft inlets.

Effect on Life Cycle Costs

- Increases control weight, complexity and cost with additional actuators and linkages for independent variable-vane control.
- Potential weight reduction by eliminating a compressor stage.

Effect on Control Complexity

- Increased computer memory for additional control software and the stall-margin/engine model.
- Actuators and linkages/hardware for independently controlled variable-vane sections.

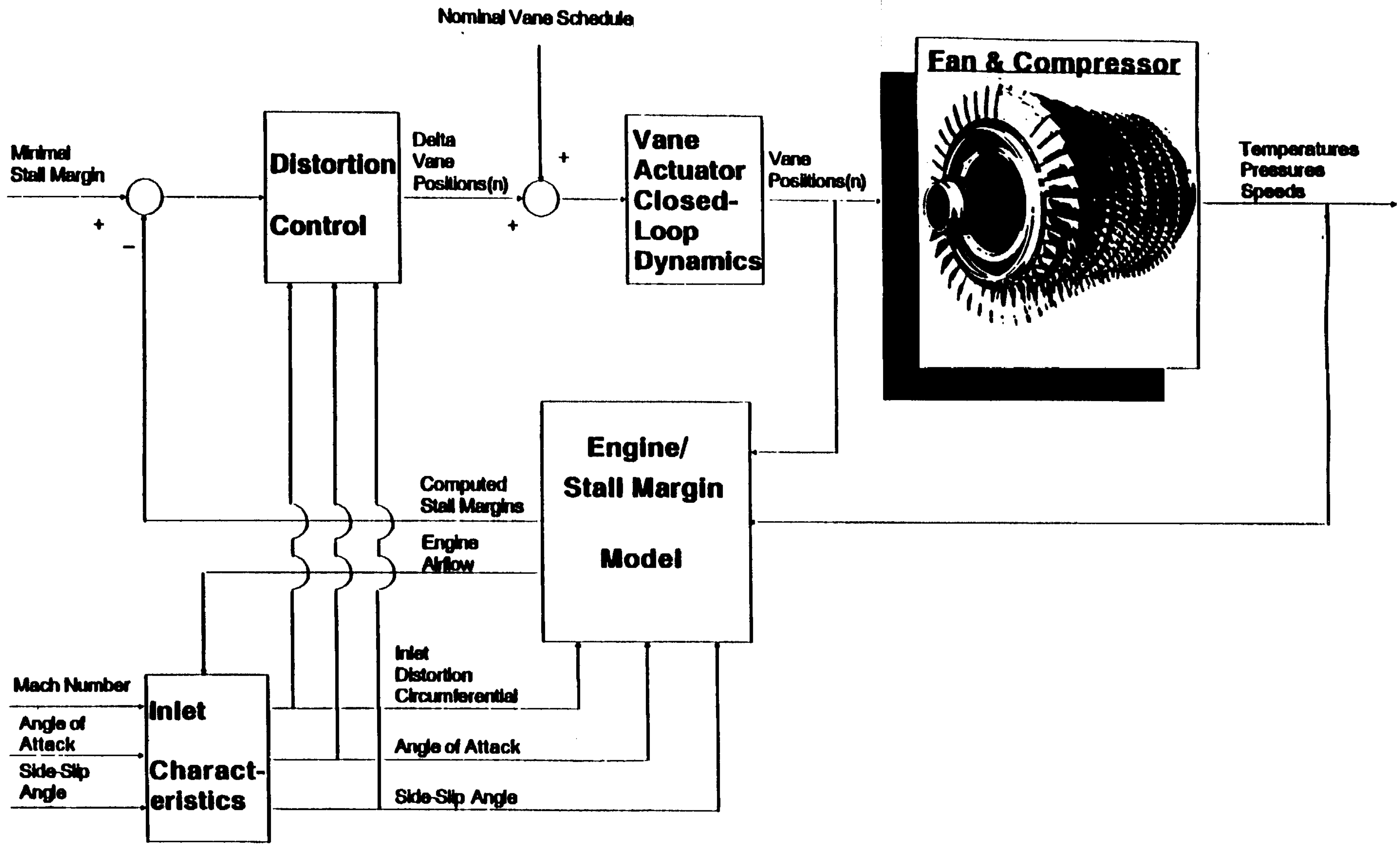

FIGURE 3-A: ENGINE DISTORTION TOLERANCE CONTROL

ACTIVE JET NOISE SUPPRESSION

CONCEPT

Background

The spectrum and intensity of turbulence is a major parameter in the emission of jet mixing noise as well as broad band shock associated noise. It is also known that an acoustic tone injected into a turbulent jet affects the turbulent intensity distribution in the jet over a broad range of frequencies (1). Low frequency sound injection with Strouhol number (fD/v) between 0.2 and 1.5 tends to increase the turbulent intensity, whereas high frequency sound injection tends to reduce the turbulent intensity over a broad range of frequencies lower than that of the injected tone. Moore (2) repeated the tests carried out by Vlasov and Ginevskiy (1) and confirmed their findings on the resulting turbulent intensity. In addition, Moore made measurements of the far-field noise and found that broad-band jet noise increased with low frequency tone injection and jet noise reduced with high frequency tone injection.

Active Control

If the results of this concept are extended by further tests so they are applicable in the jet engine environment, they can be used in an active control concept to reduce jet noise. In this concept of active jet noise suppression shown in Figure 4, near-field pressure oscillations are measured by an array of transducers such as Kulites or microphones. The signals are then fed through a band pass filter to capture the broad band jet noise which is generally in the 300 to 400 Hz range. Pressure fluctuations from one or more far-field microphones are then compared to a preset threshold. If these signals exceed the threshold, the near-field signals are phase-shifted, amplified, and used to drive an array of acoustic drivers (loudspeakers) located at specified locations in the engine tailpipe for high frequency tone injection. The far-field pressure signals are monitored and used to modify the near-field control signal for further reduction of noise emission.

Near-field measurements refer to signals at locations within one to six times the diameter of the nozzle exit plane. Far-field measurements refer to signals at locations within forty to fifty times the nozzle diameter.

Limitations

While these results of noise reduction with high frequency tone injection are encouraging, it must be noted that the tests were done with a 1.5 inch diameter nozzle at a jet exit Mach number of 0.4 to 0.6. The above tests need to be repeated and extended before assessing the benefits for jet noise reduction. The tests should be repeated with larger nozzles and in the jet exit Mach number range from high subsonic to supersonic flows. Also, current laboratory setups use off-the-shelf, relatively big and heavy acoustic drivers. For on-engine applications these components will have to be miniaturized to reduce the size and weight.

EFFECT ON PERFORMANCE

The environmental noise caused by jet mixing turbulence is reduced. Active control strategies have the potential of controlling a broad band of frequencies which is a characteristic of jet noise. Passive methods like mechanical suppressors that are predesigned hardware can only suppress a narrow band of frequencies. Active control also has the potential of reducing flow losses relative to mechanical suppressors.

EFFECT ON LIFE CYCLE COST

It results in increased weight due to the acoustic drivers, however some of the weight may compensate for the weight of mechanical suppressors. It increases control cost due to the additional hardware and software.

EFFECT ON OPERABILITY

No significant effect on stall margin.

EFFECT ON CONTROL COMPLEXITY

- 4 Near-field dynamic pressure transducers (1-2 psi Kulites).
- 4 Far-field dynamic pressure transducers (1/4 inch microphones).
- Bandpass filters.
- Additional control software.
- Phase shifters (time delays).
- Amplifiers.
- 4 Acoustic drivers (Loudspeakers).

References

1. Vlasov, Y.U. and Ginevskiy, "Generation and Suppression of Turbulence in Axisymmetric Turbulent Jet in the Presence of an Acoustic Influence, 1973 NASA Tech Trans. F 15721 June 1974.

2. Moore, C.J., "The Role of Shear Layer Instability Waves in Jet Exhaust Noise", J.F.M. 1977 Vol. 80 (2), pg. 321 - 367.

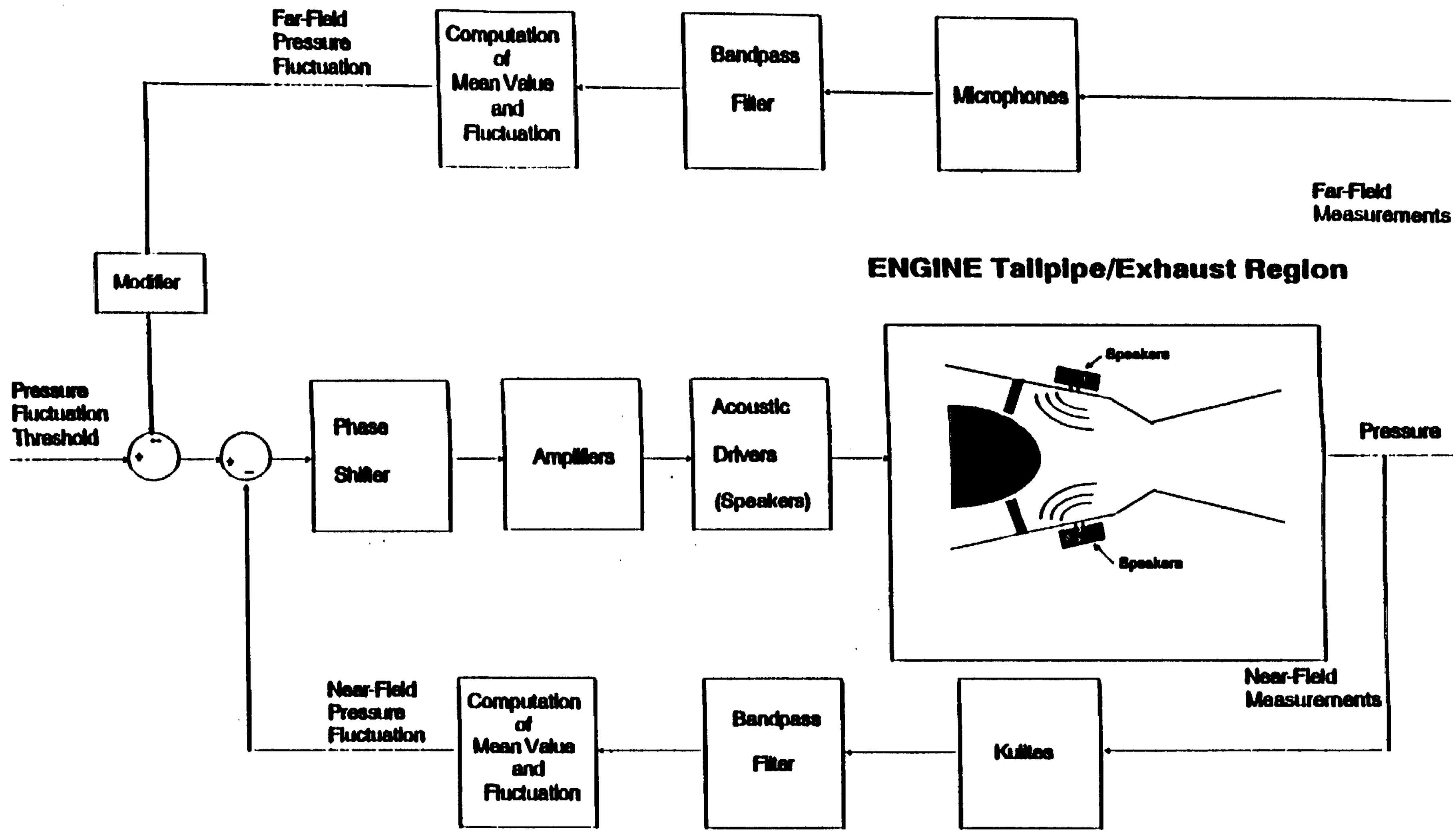

FIGURE 4-A: ACTIVE JET NOISE SUPPRESSION

ACTIVE AFTERBURNER RUMBLE SUPPRESSION

Concept

The terms rumble and screech are identified with oscillations in afterburners, and typically occur in the frequency range of 300 Hz to several kHz depending upon afterburner geometry. These instabilities are caused by the unsteady heat release associated with combustion. The unsteady heat release rate gives rise to pressure oscillations.

Several studies have demonstrated that active control via fuel modulation is a viable strategy for suppressing these oscillations. A block diagram of this concept is shown in Figure 5-A. In this scheme, the pressure oscillations are measured by appropriate sensors like Kulites. The fluctuations are then compared to a predetermined threshold. If these signals exceed the threshold, the error or the difference is fed through a control dynamic compensator and logic to generate a control signal. The signal is then amplified and used to drive an electromagnetic actuator to impart fluctuations to the afterburner fuel flow. Alternatively, the fuel modulation can be provided using one or more separate fuel injectors. This function alters the fuel/air ratio and thus the fluctuating heat release rate of the combustion and the resulting pressure fluctuations.

It has been shown in several studies that only as much as 3 percent of fuel modulation is sufficient to control the amplification of the combustor instabilities.

An alternative sensing approach is to use a CH emission sensor instead of kulites. CH is a pyrolysis hydrocarbon product that emits radiation at 446.0 nm wavelength during combustion. It has been shown to be a good measure of instantaneous heat release rate. It has also been demonstrated that a fluctuating pressure signal measured by kulites and a fluctuating heat release rate signal measured by a CH emission sensor have a high degree of correlation. Consequently, the same active control strategy as shown in Figure 5-A can be used with CH emission sensor replacing kulites.

An alternative method which is commonly found in the literature uses acoustic drivers to suppress the oscillations. The signals for these drivers are obtained by phase-shifting and amplifying the error signals. Acoustic drivers that are effective in the lower range of these frequencies are fairly big and heavy. For on-engine applications, these components will have to be miniaturized to reduce the size and weight. We selected the fuel modulation method because in the near term, it seems to have a better chance for implementation.

Effect on Performance

The noise caused by combustion generated instability is decreased and liner damage is reduced. It also has a potential of increasing afterburner thrust which is limited when screech occurs. Active control strategies have the potential of controlling a broad band of frequencies compared with a passive method which controls only a narrow band of frequencies.

Effect on Life Cycle Cost

It reduces the weight of the afterburner liner and increases its life. It increases control cost due to the additional hardware and software.

Effect on Operability

No significant effect on stall margin. It has a potential of improving afterburner lightoff characteristics.

Effect on Control Complexity

- Sensors (Kulites) to measure afterburner pressure oscillations or a CH emission sensor to measure CH emissions. CH emission sensors have to respond fast enough to capture afterburner rumble oscillations.
- Additional control software.
- Amplifiers.
- Electromagnetic actuator and valve.

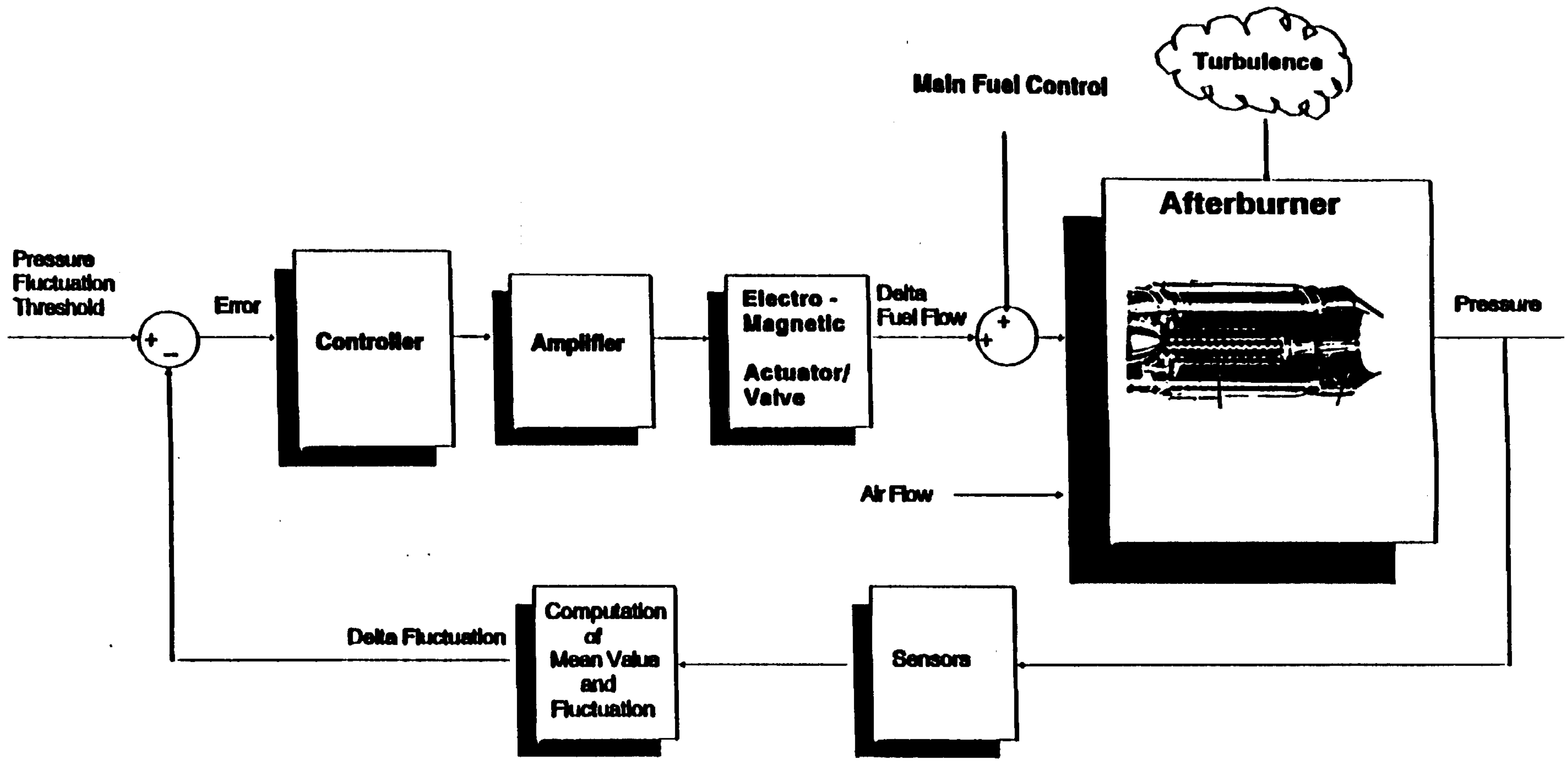

FIGURE 5-A: ACTIVE AFTERBURNER RUMBLE SUPPRESSION

ACTIVE COMBUSTOR HOWL/GROWL SUPPRESSION

Concept

The terms howl and growl are used in GEAE to describe oscillations in the main combustor. These typically occur in the frequency range of 50 to 500 Hz. Combustion instabilities manifest themselves in the form of unsteady pressure oscillations and noise. These pressure oscillations are caused by unsteady heat release rate.

A number of studies at GEAE, Cambridge (England), and France have demonstrated that active control via fuel modulation is a viable strategy for suppressing these oscillations. A block diagram of this concept is shown in Figure 6-A. In this scheme, the pressure oscillations are measured by appropriate sensors like Kulites. The fluctuations are then compared to a predetermined threshold. If these signals exceed the threshold, the error or the difference is fed through a control dynamic compensator and logic to generate a control signal. The signal is then amplified and used to drive an electromagnetic actuator to impart fluctuations to the main fuel flow. Alternatively, the fuel modulation can be provided using one or more separate fuel injectors. This function alters the fuel/air ratio and thus the fluctuating heat release rate of the combustion and the resulting pressure oscillations.

It has been shown in several studies that as little as 3 percent of fuel modulation is sufficient to control the amplification of the combustor instabilities.

An alternative sensing approach is to use a CH emission sensor instead of kulites. CH is a pyrolysis hydrocarbon product that emits radiation at 446.0 nm wavelength during combustion. It has been shown to be a good measure of instantaneous heat release rate. It has also been demonstrated that a fluctuating pressure signal measured by kulites and a fluctuating heat release rate signal measured by a CH emission sensor have a high degree of correlation. Consequently, the same active control strategy as shown in Figure 6-A can be used with CH emission sensor replacing kulites.

An alternative method which is commonly found in the literature uses acoustic drivers to suppress the oscillations. The signals for these drivers are obtained by phase-shifting and amplifying the error signals. Acoustic drivers that are effective in the lower range of these frequencies are fairly big and heavy. For on-engine applications, these components will have to be miniaturized to reduce the size and weight. We selected the fuel modulation method because in the near term, it seems to have a better chance for implementation.

Effect on Performance

The noise caused by combustion generated instability is reduced. The reduced oscillations also improve starting characteriastics.. Active control strategies have the potential of controlling a broad band of frequencies compared with a passive method which controls only a narrow band of frequencies.

Effect on Life Cycle Cost

It increases the life of the main combustor. It increases control cost due to the additional hardware and software.

Effect on Operability

No significant effect on stall margin. It has the potential of improving starting characteristics.

Effect on Control Complexity

- Sensors (Kulites) to measure combustor pressure oscillations or a CH emission sensor to measure CH emissions. CH emission sensors have to respond fast enough to capture howl/growl oscillations.
- Additional control software.
- Amplifiers.
- Electromagnetic actuator/valve or fuel injectors.

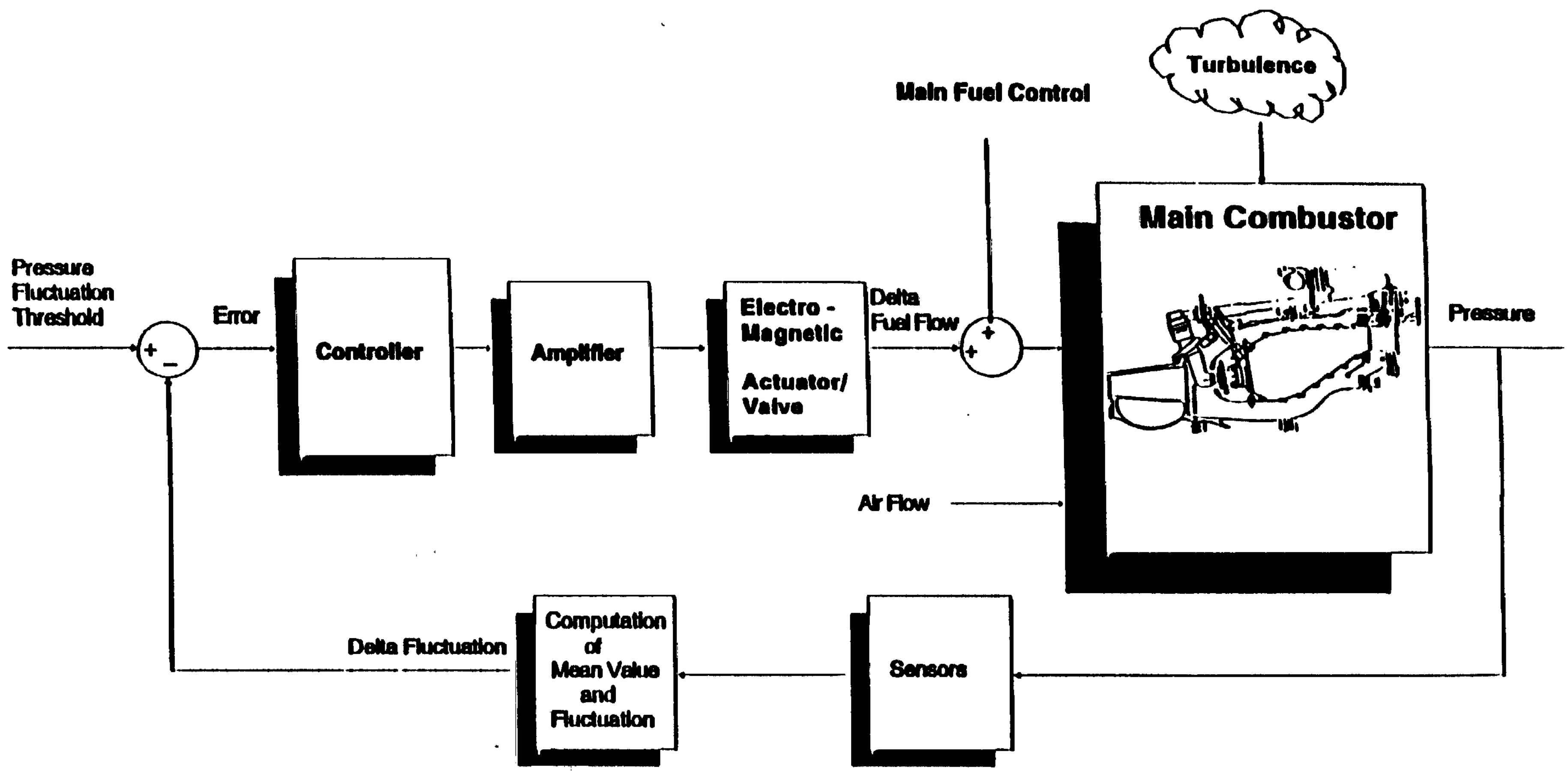

FIGURE 6-A: ACTIVE COMBUSTOR HOWL/GROWL SUPPRESSION

ACTIVE TIP CLEARANCE CONTROL

Concept

Excessive clearance between rotating blade tips and stationary casing shrouds result in reduced performance and efficiency. Digital engine controls permit the calculation of clearances by utilizing analytical models of the thermal and mechanical characteristics of the rotor and stator components as a function of measured pressures, temperatures, and speeds. These calculated clearance techniques can be complemented with direct measurement of clearances, improving initial component performance and reducing deterioration effects.

This concept, shown on Figure 7-A, provides continuous closed loop control of high and low pressure turbine rotor tip clearances, using thermal expansion or contraction of the casing to achieve the desired state. Capacitive tip clearance probes would be located at six equally spaced points around the circumference of the turbine cases to measure clearances. Data from these probes would be processed in the digital engine control to form commands to an inner loop which provides modulation of cooling and heating air flow through passages in/to the turbine casings, and therefore, control of casing temperatures. Cooling and heating air flow would be varied until the outer clearance loop was satisfied.

Effect on Performance

Tighter clearance improves turbine efficiency and SFC.

Effect on Operability

No significant effect.

Effect on Life Cycle Cost

Improved SFC results in less fuel burn.
Improves turbine blade and shroud life.
Adds sensors and control logic.

Effect on Control Complexity

Capacitive clearance sensors and interface electronics.
Air valve, actuator, and ducting.
Turbine case air manifolds.
Position feedback for air valve.
Added control logic.

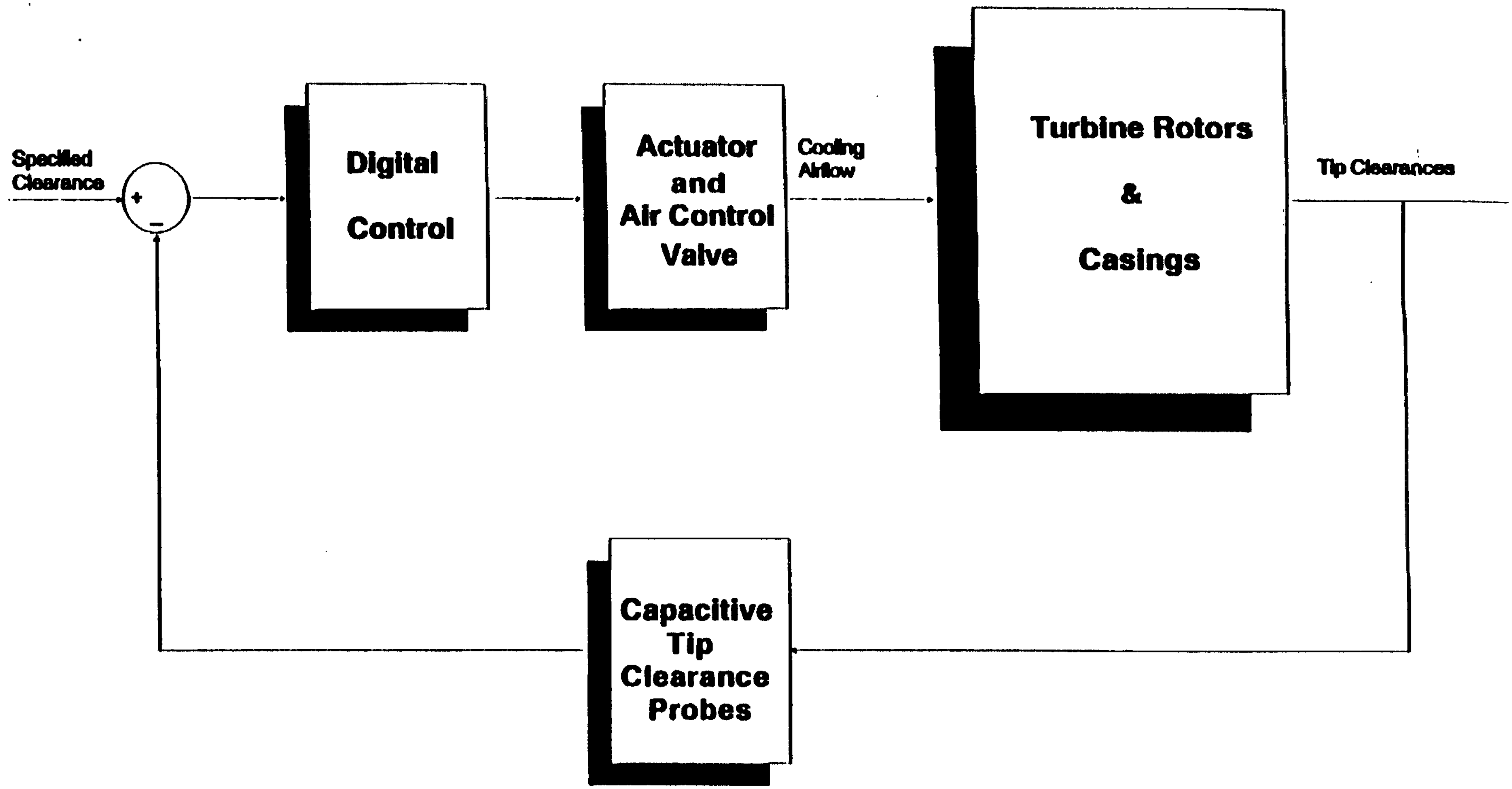

FIGURE 7-A: ACTIVE TIP CLEARANCE CONTROL

ACTIVE BURNER PATTERN FACTOR CONTROL

Concept

Combustor pattern factor is determined from gas path temperatures measured at the combustor exit. Individual temperature measurements (3 radial immersions per fuel injector) are processed in the digital engine control to determine the individual and average exit temperatures, any significant individual deviations from that average, and identification of which fuel injector's flow rate should be altered to minimize the deviation. Individual electronically controlled, motorized valves on each fuel injector would be used for trimming fuel flow. The overall total fuel flow would be maintained by the normal engine power control. Figure 8-A illustrates this concept.

Effect on Performance

Could run a higher average temperature and thrust or reduce cooling flow for SFC improvement

Effect on Operability

No significant effect on stall margin
Benefit for engine starting and combustor blowout protection with added control logic

Effect on Life Cycle Cost

Lower SFC if cooling flow reduced
Improves life of turbine nozzle and shrouds
Increases control system functionality
Cost and weight of added control logic, temperature sensors, fuel valves and motor drives

Effect on Control Complexity

Control valve and motor drive for each injector
Three temperature sensors per fuel injector at combustor exit
Position feedback for each injector valve
Control logic to identify injector valves to be modulated

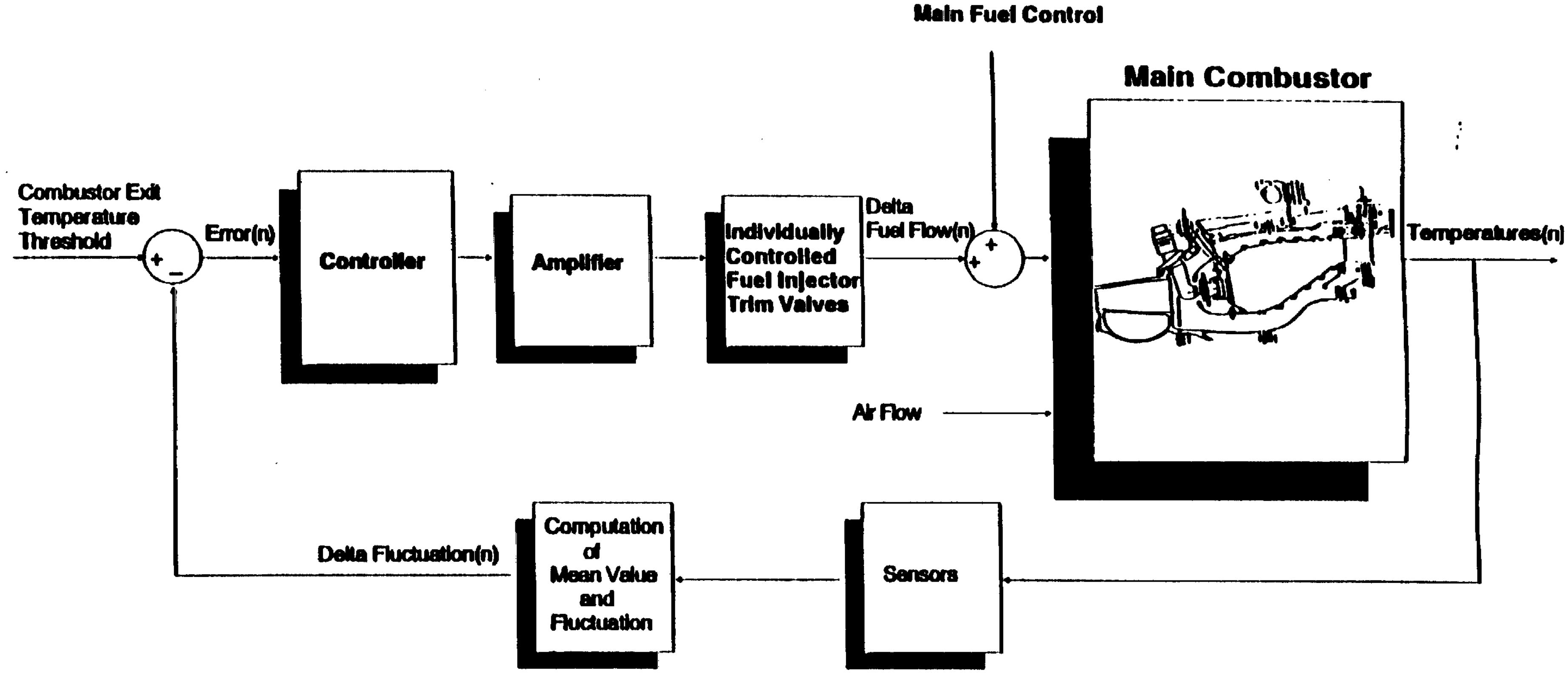

FIGURE 8-A: ACTIVE BURNER PATTERN FACTOR CONTROL

SECONDARY COOLING AIR FLOW CONTROL

Concept

SFC is enhanced by reducing excess secondary cooling flow. Secondary cooling flow is all the air extracted from the core flow path to cool the hot parts. Current design techniques size flow passages/areas to deliver the required cooling flow at maximum engine power. At lower power settings, an active control is needed to reduce cooling flow to the hot parts when their temperatures are safely below their limits. The greatest benefit occurs by modulating CDP (compressor discharge pressure) air, which is used to cool the HPT (high-pressure turbine) blades. Another benefit is to modulate the mid-compressor stage bleed, used to cool the LPT (low-pressure turbine) blades. For a 2.5 Mach cycle engine, about 6% of CDP air is used to cool the HPT blades and an equivalent 4% of compressor-inlet air is extracted from the mid-compressor stage to cool the LPT blades. An approximate performance measurement is that for every percent of CDP air used for cooling, SFC is increased by 0.5%.

As shown by Figure 9-A, the HPT and LPT blade temperatures are measured by optical pyrometers. Assuming that these temperatures are accurately sensed, cooling air to these hot parts can be modulated throughout the entire operating range. The active control will increase the cooling flow when the temperature error margin is small, and will decrease the cooling flow for a large error margin. To cool the HPT blades, a valve/actuating system is used to modulate the CDP bleed in the HPT inducer region. Only a portion of the HPT inducer cooling flow is modulated. There is a continuous amount of HPT inducer flow which provides the required cooling air at low power. The modulating circuit adds needed cooling flow for high power operation. To cool the LPT blades, mid-stage compressor bleed can be piped internally or externally and modulated by a valve system.

Effect on Performance

- SFC may be enhanced by as much as 2 percent.

Effect on Operability

- Reducing cooling flow will increase compressor compression ratio, thereby decreasing the stall margin.

Effect on Life Cycle Costs

- Increases control weight, complexity, and costs with the addition of valve/actuator systems and optical pyrometers.
- Reduced SFC will improve fuel burned.

Effect on Control Complexity

- o Computer memory and control software.
- o Valves/actuators and linkages/hardware for cooling flow modulation systems.
- o Requires two optical pyrometers.

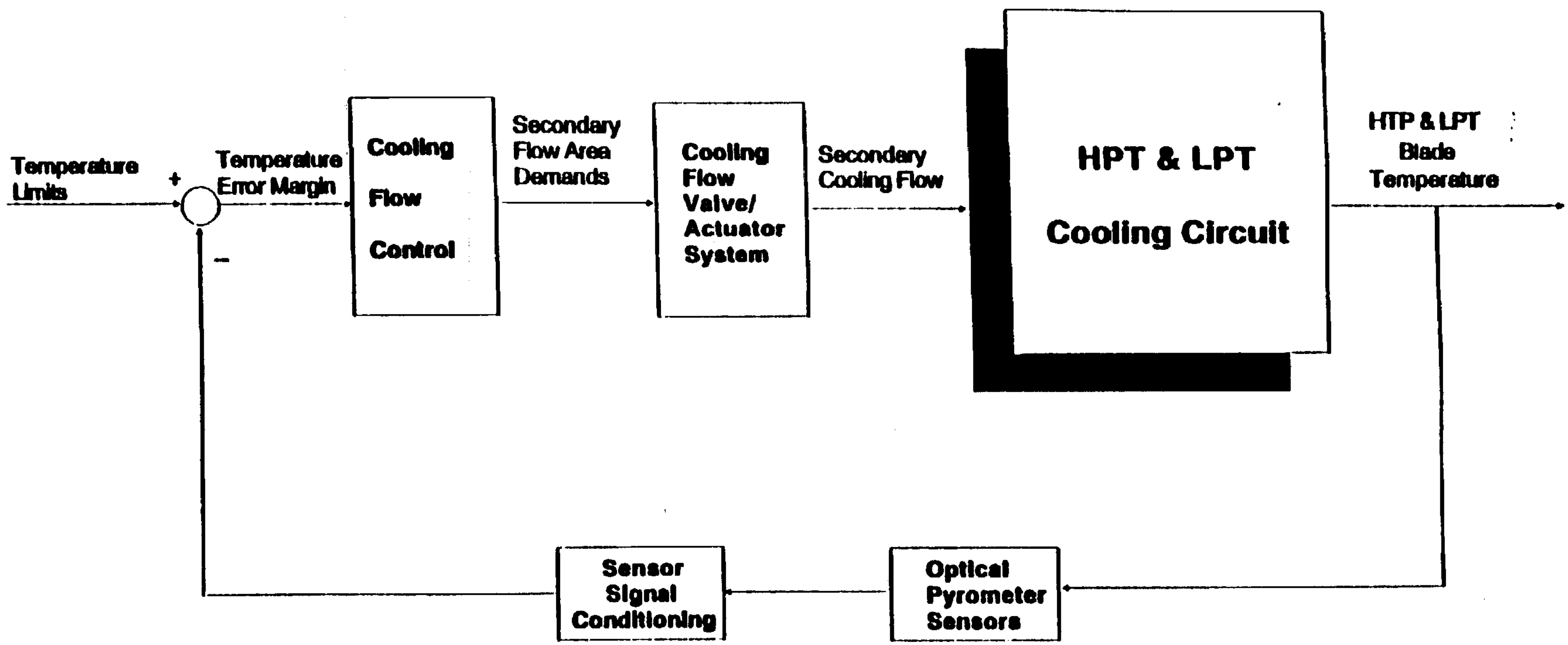

FIGURE 9-A: SECONDARY COOLING AIR FLOW CONTROL

PERFORMANCE SEEKING CONTROL

Concept

The purpose of performance seeking control (PSC) is to optimize steady-state engine performance subject to constraints. It can be used to reduce turbine inlet temperature (T41) or at constant thrust, maximize thrust at constant temperature, or minimize SFC at constant thrust.

Thrust and temperature improvements are obtained by tuning the steady-state schedules (i.e., N1, dP/P and/or EPR) to account for variations of engine performance with respect to the nominal engine design. Engine-to-engine performances vary because of manufacturing tolerances, engine life deterioration, sensor tolerances, and actuator tolerances.

PSC can be used to improve SFC at part power by tuning schedules to account for (i) engine quality and deterioration variations, and (ii) compromises in the pre-programmed schedules. PSC studies show that no significant improvement in SFC is possible due to quality and deterioration variations. This is because the nominal schedules, which were optimized for the nominal engines, have been found to be optimal for the off-nominal engine as well. Note, however, that the SFC of a deteriorated engine will be higher than the SFC for a new engine, although the optimum schedules for the two engines may be identical. SFC improvements are achieved by removing compromises in corrected parameter schedules at specific operating conditions such as: altitude, Mach number, ambient temperature, power setting, bleed, and power extraction.

The heart of PSC is a constrained gradient search module which minimizes T41 or SFC at constant thrust. Constraints on stall margins, engine speeds, and other engine variables are used to ensure safe engine operation. Prior to optimization, the component level model (CLM) is updated, by the tracking filter, to fine tune its computed output to match the engine sensed outputs. PSC can also be used to optimize an integrated flight/propulsion control (IFPC) system, in which case the benefits will be greater than when used with the engine alone. PSC can be used for an IFPC system to minimize fuel consumption or by varying aircraft velocity and fuel consumption together, the maximum range can be optimized. Figure 10-A shows the PSC concept for an IFPC system.

Timing studies of PSC on a variable cycle engine show that the tracking filter takes less than 0.1 sec to complete its update, and the complete optimization process requires less than 2.0 sec. These numbers are valid assuming a single-pass computation time of 2 msec for the embedded engine model.

Effect on Performance

The performance ratings shown here are for a PSC applied to the engine only (not including aircraft). Using a IFPC format should augment the performance further.

- At maximum power, T41 reduced 20 to 30 degrees Fahrenheit.
- At part power, SFC reduced 2 to 3 percent.

Effect on Life Cycle Cost

A reduction of 25 degrees Fahrenheit in the average value of T41 translates to a 20 percent increase in engine life cycle.

Effect on Operability

No significant change when reducing SFC or T41 at constant thrust; however, stall margin can be an optimized if desired.

Effect on Control Complexity

No additional engine hardware is needed, except for computer memory and software. PSC for an engine control requires approximately 25K bytes of memory. Of this, 10K is for the CLM. The IFPC format would require approximately an additional 25k bytes for the aircraft tracking filter and aircraft model, for a total of 50k.

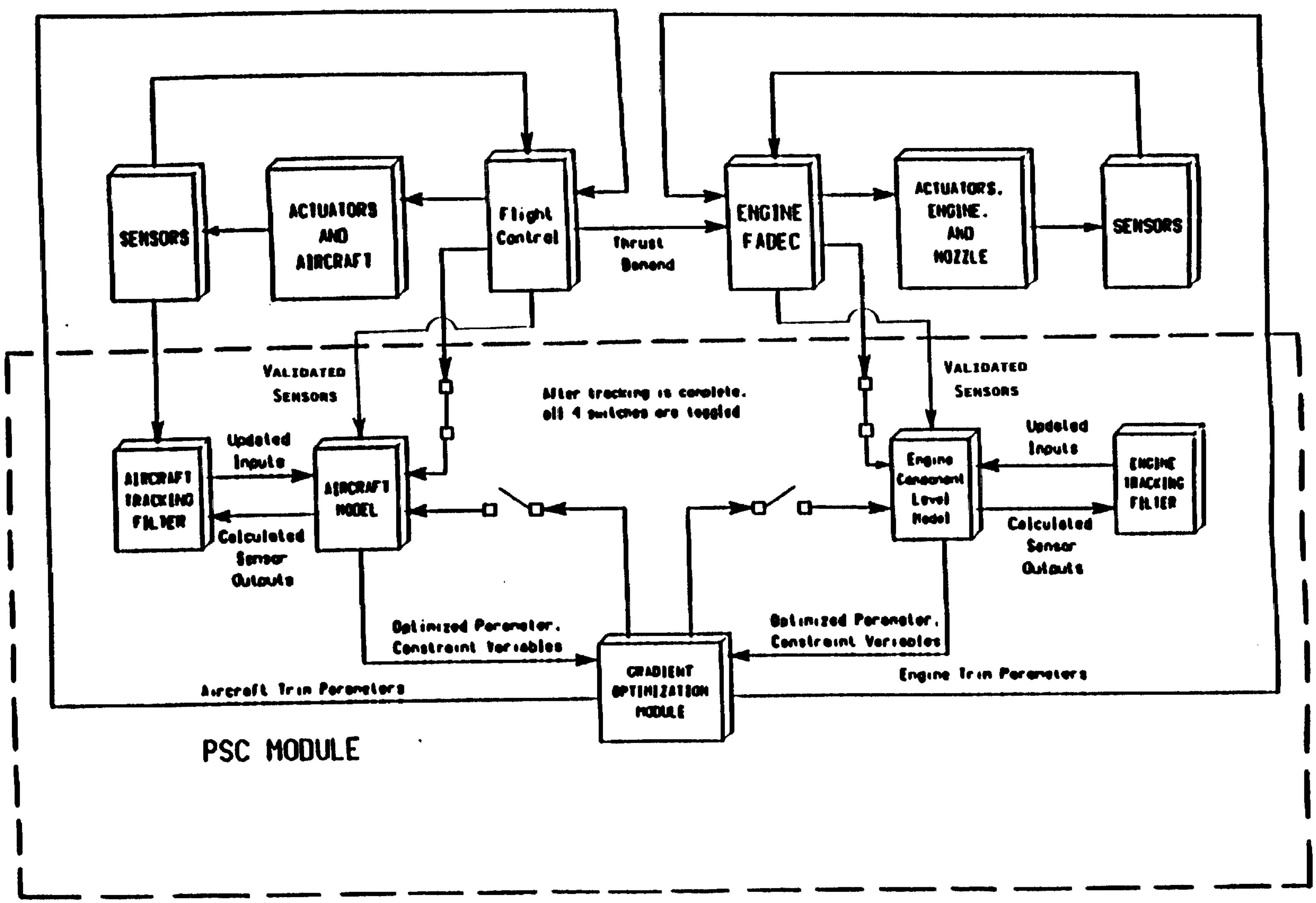

FIGURE 10-A: PERFORMANCE SEEKING CONTOL IN IFPC SYSTEM

INTELLIGENT DIAGNOSTIC/CONTROL SYSTEM

Concept

The Intelligent Diagnostic/Control System would combine and build on the concepts explored during the Performance Seeking Control (PSC), Analytic Redundancy Technology for Engine Reliability Improvement (ARTERI), and Survivability Biased Engine Control (SuBEC) programs. The control would provide the following functions:

- o Optimization of SFC and/or Temperature at a given thrust
- o Condition Monitoring of engine and control system
- o Accommodation of faults/damage in engine or control system

A very real though indirect benefit derived from achieving these functions is the reduction in engine design margins that results when such tight control of individual engines under a broad range of conditions is realized.

A comprehensive, Component Level, real time model of the engine constitutes the heart of the control system. This model, driven by a minimum number of sensors, can provide estimates of sensor outputs which can be used to replace failed sensors (analytic redundancy), and it provides an on-line vehicle for perturbation exercises when performing optimization or fault/damage reconfiguration functions. A continuous update function would maintain the correlation between the model and the actual engine as the engine "ages" in service.

Model data would be constantly scanned by an "optimizing" routine to determine if engine geometry can be trimmed to deliver the required thrust in a more efficient manner. Simultaneously, a higher order monitoring function, based on a-priori criteria, or perhaps Artificial Intelligence, would note when excessive model update correction was required or significant discrepancies occurred between sensed input, estimated performance, and expected values. Any of these symptoms would indicate that a fault had occurred. Logic routines would identify the location of the fault and initiate the proper accommodation or reconfiguration measures to retain engine performance to the extent possible.

Appropriate interfaces with other subsystems (such as aircraft flight controls), cockpit displays, and storage of data for subsequent ground maintenance and trending would also be incorporated.

Effect on Performance

Provides improved SFC for most engines
Provides continued operation for many failure situations
Permits use of lighter engines for same thrust

Effect on Operability

Can improve stall margin for most engines

Effect on Life Cycle Costs

Improves Maintainability
Can provide lower temperature operation/longer engine life
Use of engine model could reduce the number of sensors required or the number of redundant control channels needed for reliability
Additional digital processing equipment required

Effect on Control Complexity

Appropriate sensors
Digital processing equipment
Appropriate interface provisions
Added cockpit displays

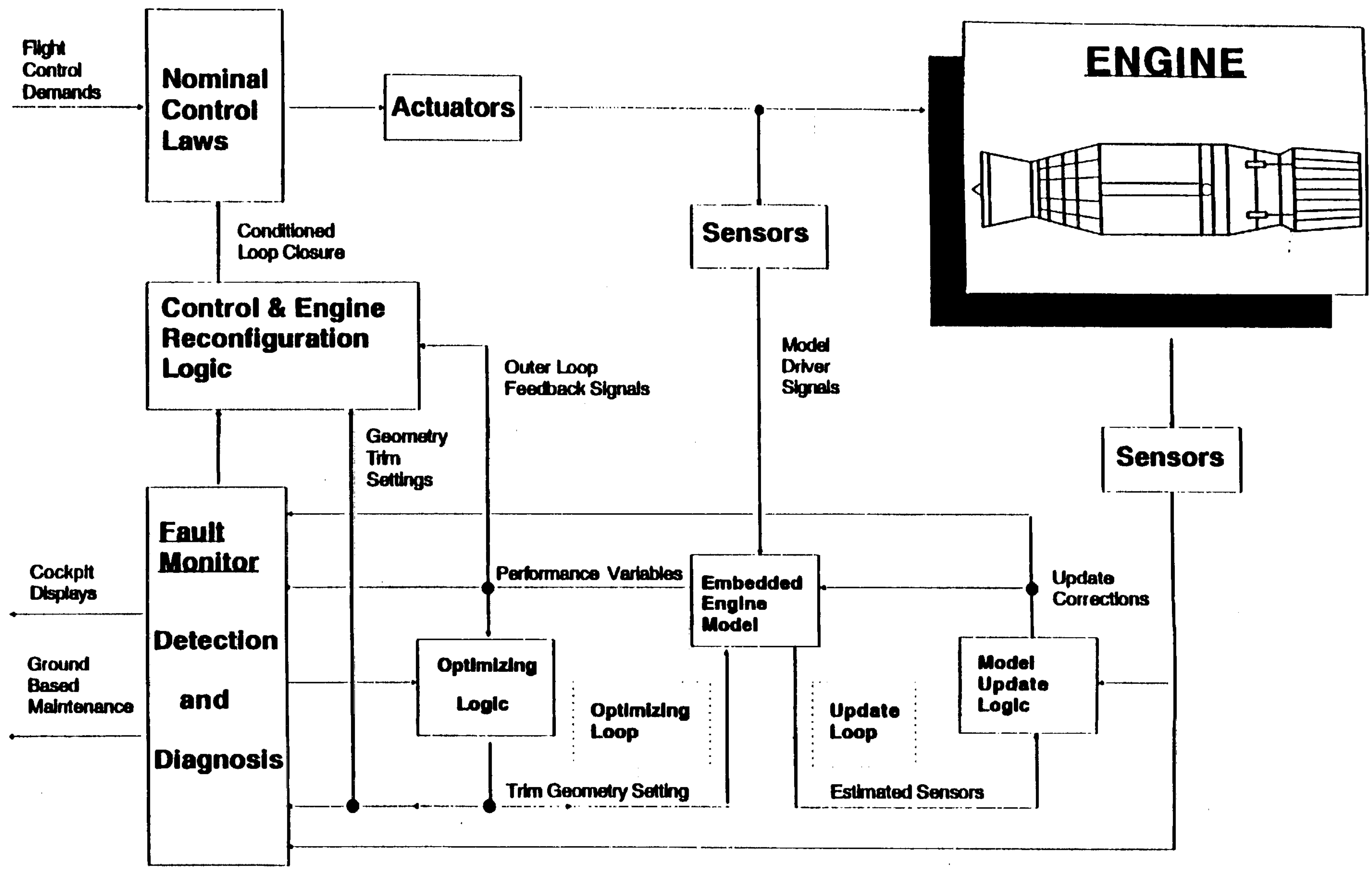

FIGURE 11-A: INTELLIGENT DIAGNOSTIC/CONTROL SYSTEM

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13. ABSTRACT ***(Maximum 200 words)***

The application of advanced control concepts to airbreathing engines may yield significant improvements in aircraft/engine performance and operability. Screening studies of advanced control concepts for airbreathing engines have been conducted by three major domestic aircraft engine manufacturers to determine the potential impact of concepts on turbine engine performance and operability. The purpose of the studies was to identify concepts which offered high potential yet may incur high research and development risk. A target suite of proposed advanced control concepts was formulated and evaluated in a two phase study to quantify each concept's impact on desired engine characteristics. To aid in the evaluation specific aircraft/engine combinations were considered: a Military High Performance Fighter mission, a High Speed Civil Transport mission, and a Civil Tiltrotor mission. Each of the advanced control concepts considered in the study are defined and described. The concept potential impact on engine performance was determined. Relevant figures of merit on which to evaluate the concepts are determined. Finally, the concepts are ranked with respect to the target aircraft/engine missions. A final report describing the screening studies has been prepared by each engine manufacturer. Volume 2 of these reports describes the studies performed by GE Aircraft Engines.

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